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GEOLOGICAL MAGAZINE

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A Revision of the Fauna of the North Welsh *Conocoryphe viola* Beds implying a Lower Cambrian Age

By B. F. HOWELL and C. J. STUBBLEFIELD [1]

(PLATES I AND II)

ABSTRACT

Fossils collected during the past sixty years from the uppermost division of the approximately 2,000 ft. thick Llanberis Slates have been re-examined. All but one fossil came from the famous Penrhyn Quarries at Bethesda, Caernarvonshire. The fauna is described as containing *Pseudatops viola* (H. Woodward), *Eodiscus* sp., cf. *Protolenus howleyi* (Walcott), *Hyolithes* cf. *hathewayi* G. F. Matthew, *H.* sp., and a fragmentary crustacean. The last offers no evidence of age but the remainder are considered to indicate a high Lower Cambrian horizon. Illustrations of some of these fossils are given for the first time. The *Hyolithes* is interpreted as carrying a pair of fin-like skeletal outgrowths and the morphological significance of these is discussed in a statement which comments on the obscure systematic position of the Hyolithidae.

1. INTRODUCTION

BENEATH the thick transgressive Bronllwyd Grits of northern Caernarvonshire lie the Llanberis Slates estimated as being 2,850 feet in thickness at Bethesda by J. J. Evans (1883) and as 2,060 feet by I. Griffiths (1935). These Bronllwyd Grits have yielded no fossils and are described as overlain by Maentwrog Slates (D. Williams, 1930); their age has been conjectured as Upper Cambrian by T. O. Morris and Fearnsides (1926), also by D. Williams (1930), though more recently O. T. Jones (1938, p. lxvii) has suggested that of the Harlech Grits as more probable. The remarks which follow would also leave a Middle Cambrian age as a further possibility (see also Greenly, 1944, 1946).

From Nantlle in the south-west to beyond Bethesda in the north-east the Llanberis Slates have long been sought by quarrying and mining because of their excellent quality, and different lithological characters, colour and degree of cleavage have caused the slate bands to be given particular names. Their geological sequence in the well-known

[1] Submitted for publication with permission of the Director, Geological Survey and Museum.

Penrhyn Quarry, Bethesda, was recorded in 1934, and was illustrated in plan and section by Griffiths (1935).

A bed, 120–150 feet in thickness, known as the Upper Green Slate, forms the stratigraphically highest part of the slate series cropping out immediately beneath the Bronllwyd Grits in the eastern part of the quarry. This bed, which is infrequently worked, in 1887 yielded to two quarrymen the first trilobite to be recognized in the Llanberis Slates. The cleavage where the fossils were found is nearly coincident with the bedding, and the quarrymen, R. E. Jones and R. Lloyd, took counterparts of the slightly distorted trilobite, which they had collected, to J. J. Dobbie, Professor of Chemistry at University College, Bangor. He accompanied the men to that part of the quarry known as the Crimea, which was the scene of their discovery, and was rewarded by himself finding another trilobite cephalon among the green slate debris.

In the following year these two examples formed the basis of the description of *Conocoryphe viola* by Henry Woodward (1888), the specific name being dedicated to the wife of Professor Dobbie. In his description, Woodward termed the parent strata " Longmynd group " and the Shropshire Longmyndian rocks at that time were considered to be equivalent in age to the Solva Group of South Wales which, even then, had yielded Middle Cambrian fossils. Hicks, in the published discussion to Woodward's paper, expressed the opinion that the Penrhyn fossiliferous horizon was Lower Cambrian and this view was repeated by McKenny Hughes in 1889. At the period when Woodward wrote, British Lower Cambrian fossils were virtually undescribed, though later in that same year Lapworth (1888) announced the discovery of an Olenellid trilobite in Shropshire. Walcott (1890, p. 581), however, two years afterwards recalled that in 1888 he had visited Penrhyn Quarry and had seen *C. viola* associated with a species of *Hyolithes* and from " the weight of stratigraphical evidence " he was inclined to include these beds in his *Olenellus* Zone which by then had lately acquired its present Lower Cambrian status.

Nevertheless, some more recent writers have tended, with varying degrees of confidence, to regard the Upper Green Slate as being of Middle Cambrian age ; furthermore, the original generic reference of Woodward's species to *Conocoryphe* and a subsequent changing of the generic reference to *Solenopleura* (Lake, 1931) have appeared to confirm that age. The presentation to the Geological Survey and Museum in 1936 by the late Major I. Griffiths of a newly found specimen of *C. viola* caused the present authors in 1937 to commence a re-examination of all the available fossils and supposed fossils collected from the Llanberis Slates.

This work led to the opinion that the correct generic comparison of Woodward's species was with *Pseudatops reticulatus* (Walcott), a form

of which in 1936 was described by Cobbold from limestones in the top few feet of the Shropshire Lower Cambrian. Furthermore, as will be read in the following pages, associated fossils from the Upper Green Slate of Penrhyn Quarry resemble forms known elsewhere from accredited Lower Cambrian strata and thus appear to substantiate this view of a Lower Cambrian age.

2. Remarks on the Genera Atops and Pseudatops

The genus *Atops* has had a chequered history both in nomenclatorial status and in stratigraphical position. It was named as a monotypic genus by Emmons in 1844 on the evidence of a poorly preserved specimen of *A. trilineatus* (Plate I, fig. 4, of this paper) found by Asa Fitch near North Greenwich in New York State, associated with *Elliptocephala asaphoides*. These two species, both erected by Emmons, were the earliest described fossils, from any strata which we now know to be of Lower Cambrian age. They were, moreover, among the supposed characteristic fossils of Emmons' Taconic System, a system from which the Ordovician elements were later separated. The indifferent nature of Emmons' original material of *Atops trilineatus* led James Hall (1847) to consider the species as a synonym of the Utica Shale *Calymene* (=*Triarthrus*) *becki*, but in the year following, 1848, this opinion was disputed by Haldeman. Emmons, after finding new material of his genus, strengthened his case for the retention of the name *A. trilineatus* by the description of a fairly complete individual now unfortunately lost. Walcott, nevertheless, in 1886 referred *A. trilineatus* to *Ptychoparia* and later (1887) to *Conocoryphe*. In both 1886 and 1887 he recorded the horizon as Middle Cambrian for at that time the *Olenellus* Fauna was considered by most American geologists to be younger than that of *Paradoxides*. By 1889, however, Walcott had convinced himself of the justice of Brögger's claim from European evidence that the American sequence had been misread and he recognized *C. trilineata* as " one of the best marked forms in the New York Lower Cambrian ". With better material of the species before him in 1890 he not only refigured Emmons' type but gave drawings of a beautifully preserved additional specimen (a photograph of this specimen by Dr. C. E. Resser is reproduced here as Plate I, fig. 3) and another free cheek which comprised the lateral part of the marginal rim and the genal spine.

He also illustrated and described a new species, which he termed *C. reticulata*, from Salem, New York, likewise said to be associated with *Elliptocephala asaphoides*. A photograph of the type of *C. reticulata*, again thanks to the kindness of the late Dr. C. E. Resser, is given here as Plate II, fig. 2.

Both *A. trilineatus* and *A. reticulatus* were attributed to *Atops* by G. F. Matthew in 1899, but it was not until 1936 that the genus was recorded outside America when Cobbold described a cranidium from the Lower Cambrian *Eodiscus bellimarginatus* Limestone of Comley, Shropshire (refigured here, Plate II, fig. 1). More recently, Lake (1940) has restricted the concept of *Atops* by separating *A. reticulatus* as the type of his new genus *Pseudatops*. He recognized four differences in structure :—

(1) *The Position of the Front of the Glabella.*—In *Atops* this reaches the marginal furrow whilst in *Pseudatops* it encroaches upon the marginal rim.

(2) *The Nature of the Marginal Rim and Marginal Furrow.*—In *Atops* this rim he considered to be narrow (but see Plate I, fig. 3) and upturned, separated from the glabella by a strong pre-glabellar furrow, whereas in *Pseudatops* the rim is stated to be flat and downturned in front of the glabella.

(3) *The "Facial Suture".*—In *Atops* this suture passes across the marginal furrow to leave only the front third of the marginal rim on the cranidium (despite Walcott's description, this feature is not well seen on the specimen illustrated here as Plate I, fig. 3), but in *Pseudatops* the suture, if present at all on the dorsal surface, only cuts off a narrow strip of the marginal rim and the genal spine.

(4) *Ornament.*—In *Atops* this is granular, but in *Pseudatops* it is a network of raised lines.

3. *Pseudatops viola* (H. Woodward)

Plate I, figs. 1, 2, 5 ; Plate II, fig. 3

1888. *Conocoryphe viola*, H. Woodward, *Q.J.G.S.*, xliv, p. 74, pl. iv, figs. 1–3.

1931. *Solenopleura viola* Lake *partim*, *Palaeont. Soc.*, p. 141, pl. xv, figs. 6–8 (*non* 9), pl. xvi, figs. 1, ? 2 (*non* 3).

Lectotype (here chosen) the specimen (in counterpart) figured by Woodward, pl. iv, fig. 1, of which the internal mould was figured by Lake, pl. xv, fig. 8, as also a plaster cast made from the external mould, pl. xvi, fig. 1 ; Bangor University College Collection on loan to Geological Survey and Museum (Plate I, fig. 2). Woodward's figure was constructed from the two moulds.

Material (all distorted).—Four cephala with parts of thorax in position of life, two in counterpart (two B.U.C. Coll., collected 1887–8, of these one is the lectotype and the other was also figured by Lake, pl. xv, fig. 7, the other two are in the E.B. Luxmoore Coll. 1889, B.M. (N.H.). In 37745, In 37746, here Plate I, fig. 5).

Three detached cephala—B.U.C. Coll., collected J. J. Dobbie, 1888,

figured by Lake, pl. xv, fig. 6 and here Plate II, fig. 3 ; B.M. (N.H.) In 37745, E. B. Luxmoore Coll., 1889 ; Nat. Mus. Wales, 27.110.640, collected G. J. Williams.

Two partial cephala with thoraces (T. McKenny Hughes Coll., 1889, Sedg. Mus. A 1163, 1164.

One thorax in counterpart (B.U.C. Coll., figd. Lake, pl. xvi, fig. 2).

One fairly complete individual (Geol. Surv. Mus. 54912, I. Griffiths Coll., 1936), here Plate I, fig. 1.

There are also two fragmentary examples in the Bristol Museum C 2984 and C 2985, 2989 (counterparts).

Revised Description.

Present length of G.S.M. specimen numbered 54912 *circa* 90 mm., of which cephalon occupies *circa* 35 mm., thorax 48 mm., and pygidium 7 mm.

Surface of entire test, covered with grains of a chlorite (?) mineral sometimes rusty weathered, reticulate structure occasionally indefinitely suggested.

Cephalon.—Considerably wider than long, semi-ovate in outline, convex, cheeks inflated, axial furrows and occipital furrow deep and glabella probably rather strongly inflated. Marginal rim separated from rest of cephalon by a marginal furrow and terminating posteriorly in a short backwardly directed spine. *Glabella* long, reaching marginal furrow in front and narrowing the rim anteriorly ; probably a third total width and narrowing slightly forwards ; with three pairs of backwardly directed furrows of which the front pair probably originates laterally in front of mid-point between occipital furrow and front end ; all strongly incised, particularly the hind pair ; there are suggestions of a more anterior pair of furrows halfway between the front and the most anterior pair of the incised glabellar furrows. " *Ocular* " *ridge* proceeds from glabella some distance in front of most anterior incised glabellar furrow, crosses the depression of which axial furrow forms a part, skirts front end of cheek inflation and dies out before reaching lateral marginal furrow.

Occipital ring of fairly even length.

Cheeks bounded posteriorly by deeply incised pleuroccipital furrow which appears to meet the marginal furrow in a rounded angle ; the inflation is such that the cheeks usually have cracked under compression. Posteriorly there seems to be an extension of the hind margin rather more than half-way out from the axial furrows and probably corresponding to the articulation-fulcrum.

Eyes and " *Facial sutures* " not distinguishable.

Hypostome and *ventral plates* unknown.

Thorax consisting of seventeen segments. The axis slightly narrower

than pleura, sub-parallel as far as eighth or ninth segment and from thence narrowing slightly, moderately convex, and with suggestions of tubercles on axial rings, particularly in more anterior rings. The pleurae are deflected downwards near their outer ends ; bluntly pointed but not prolonged into spines ; each has a wide, moderately impressed groove deepening at the fulcrum and remaining deep to the end ; the posterior margin of the groove is ridged.

Pygidium small, of sub-ovate outline, margin entire ; wider than long with a raised axis rounded posteriorly showing one and perhaps two transverse furrows ; lateral portions imperfectly known, suggestions of a furrow parallel to anterior edge.

Remarks.—In the genotype of *Solenopleura*, *S. caniculata* Angelin,[1] the number of thoracic segments is unknown but in Salter's species *Conocoryphe applanata* and *C. ? variolaris*, both nowadays referred to *Solenopleura*, on the authority of Lake the number is fourteen. If, as we believe, the Griffiths' specimen is correctly referred to the species *viola*, it seems to discredit Lake's statement (1931, p. 142) that this species has but fourteen thoracic segments.

The Griffiths' specimen furthermore shows a short pygidium quite distinct from that attributed to *C. viola* and figured by Lake as pl. xv, fig. 9 ; that pygidium has two thoracic segments attached and perhaps a third, but these do not seem closely to resemble those of *P. viola*.

The specimen figured by Lake, 1931, pl. xvi, fig. 3, which shows a pair of palpebral lobes is discussed later, but it is not considered to be congeneric with the syntypes of *Conocoryphe viola* ; Lake's opinion (1931, and 1940, p. 292), however, is upheld that the species *viola* can no longer correctly be referred to *Conocoryphe*.

In our opinion, bearing in mind the characters of the glabella, cheeks with " ocular " ridges, the thoracic segments and the pygidium, the appropriate generic assignment is with *Atops* or with *Pseudatops*. It may be noted that the most anterior pair of glabellar furrows are relatively nearer the " ocular " ridges in *Atops* (Pl. I, figs. 3, 4) than in *Pseudatops* (Pl. II, fig. 2). In *P. viola* the most anterior of the three pairs of incised furrows is even further removed from the " ocular " ridges. Nevertheless, the number and character of the thoracic segments and the general aspect of the pygidium (Pl. I, fig. 1) resemble *Atops trilineatus* (Pl. I, fig. 3) ; in *Pseudatops*, the thorax and pygidium, hitherto are undescribed. The front of the cephalon of *P. viola* more closely resembles that of *Pseudatops*, particularly in the " ocular " ridge (see Pl. I, fig. 2 ; Pl. II, fig. 3) and in the preglabellar reduction of the marginal rim as portrayed in Plate I, fig. 2. Accordingly, the species has been referred to *Pseudatops* rather than to *Atops*.

[1] Selected S. A. Miller, 1889, not, as usually stated, *S. holometopa* Ang. selected Vogdes, 1890.

McKenny Hughes (1889, p. 11) has recorded that the Upper Green Slate fossils " appear on distorted bed faces, generally lying within 5° or 10° of the cleavage planes ".

Distortion and shearing have been such that not infrequently the glabella has been burst at its hind or front end (Plate I, figs. 1, 2, 5) and, with Lake, we agree that " the small circular raised prominence " in front of the glabella mentioned in Woodward's original description is the result of fracture.

It is significant that of the specimens examined, almost half appear to have been fossilized as completely articulated skeletons ; that they have not been preserved as complete individuals is largely the misfortune of collecting coupled with the vicissitudes of cleavage and jointing. This is in marked contrast to the state of the trilobites in the Comley limestones which are almost invariably found disarticulated, and it points to deposition at Penrhyn in calm waters relatively free from wave action. The preservation of the Hyolithid described below also supports that view.

4. *Eodiscus* sp.

1931. *Solenopleura viola* Lake *partim*, *Palaeont. Soc.*, p. 143, pl. xv, fig. 9.

Material.—A pygidium with thorax attached (possibly with cephalon folded beneath it and buried in the matrix [1]), in counterpart dated 27th December, 1889, in the collection of the Free Public Museums, Liverpool, stated by Lake, op. cit., to have been collected by R. Lloyd.

Thorax, two segments seen attached to front of pygidium and a third segment appears to lie inverted anterior to these as if the trilobite were enrolled. Axis, convex, appears to be wider than the individual pleurae which appear to be grooved ; the articulating half-ring of the more anterior segment is visible.

Pygidium, at present 8 mm. in length, subtriangular in outline. Axis tapering posteriorly, convex, probably originally of width equal to lateral lobe and extending back to marginal furrow which is surrounded by a narrow flat rim which is not continuously preserved. Axis shows five furrows up to mid-length from behind forwards, originally probably with ten or more rings. Axial tubercles not definitely visible but a ridge now running along axial line of the axis may indicate the former presence of a series of tubercles on the crests of the axial rings. Moreover, when the negative impression is viewed with a bottom right source of light, seven axial tubercles are suggested.

[1] X-ray photography by Mr. P. A. Sabine failed to confirm this suggestion but the mineral composition of the Trilobite remains did not form differences likely to be taken up by X-rays.

Remarks.—This *Eodiscus* pygidium shows some features in common with *E. bellimarginatus* (Shaler and Foerste), if the present apparent width of its axis is due to compression of a very elevated structure and if the suggestion of axial tubercles is real. That species was described from North Attleborough (Massachusetts) and was later reported by Walcott from Manuel's Brook (Newfoundland) and by Lake and Cobbold from Comley (Shropshire).

There are also resemblances with *E. speciosus* (Ford) originally described from Troy (New York) and Bic Harbour (Canada) and later reported from North Attleborough and likewise by Lake and Cobbold from Comley. Its distribution has been recently found to be greater by Samsonowicz in Poland, by R. and E. Richter and Schwarzbach in Silesia, and by R. and E. Richter in Spain.

Both these species are referred by R. and E. Richter (1941, p. 27) to their new subgenus of *Eodiscus* (*Serrodiscus*), of which all the known species come from the highest Lower Cambrian. One feature of this subgenus is the large number of axial rings on the pygidium (eight to fourteen or more).

Kobayashi, however, publishing in 1943 without knowledge of Richter's publication, retained *E. bellimarginatus* in *Eodiscus* and made *E. speciosus* the genotype of a new genus *Paradiscus*. Kobayashi renamed Lake and Cobbold's *E. speciosus*, *Paradiscus robustus* Kobayashi (1943, p. 38 ; 1944, p. 51), on account of their greater convexity of the glabella and cheeks, larger glabella and a small lunate preglabellar depression. The feature distinguishing between *Eodiscus* and *Paradiscus* is the presence of occipital and genal spines on the cephalon of the former. In the opinion of the writers it is doubtful whether such a distinction has more than subgeneric value. The cephalon of the Penrhyn form, however, is unknown and pending its discovery both subgeneric and specific determination is now withheld.

Lake has stated (1931, p. 143) that in the Welsh specimen the appearance of segmentation is entirely fictitious. He continues : " In some lights it seems remarkably real, in others it is clear that it is a wrinkling which is continued across axis and lateral lobe even on to the matrix itself." We are unable to agree with these opinions, though we support the view expressed by Lake that the " original features are evidently masked ", and in this connection we recall that the Richters have devoted several pages of discussion (op. cit., pp. 58–60, pl. ii, fig. 22A) to the effects of folding and regional metamorphism on external and internal impressions of Eodiscid skeletons.

McKenny Hughes (1889, p. 9) stated that he had found fragments of another trilobite species, smaller than *Conocoryphe viola* in the Green Slate not far below the Bronllwyd Grit—these specimens have not been traced ; they may belong to the present species.

5. Cf. *Protolenus howleyi* (Walcott)

1931. *Solenopleura viola* Lake *partim*, *Palaeont. Soc.*, p. 142, pl. xvi, fig. 3.

Material.—Three cranidia, all compressed obliquely from front to back. Sedg. Mus. A3235A and B (figured Lake) : Imp. Coll. Sci. A. C. Young Coll. and doubtfully Sedg. Mus. A1165 external moulds only.

Description.—Cranidium moderately convex, axial furrows and occipital furrow deep, marginal rim moderately wide and slightly convex. Glabella tapering towards front, just touching marginal rim which it does not indent ; probably about one-third cranidial width posteriorly ; with three pairs of backwardly directed shallow furrows, of which the two posterior are strongest. Ocular ridge proceeding outwards from just in front of most anterior glabellar furrow to merge into convexly curved palpebral lobe and to terminate just in front of pleuroccipital furrow. Fixed cheeks bounded posteriorly by well incised and wide pleuroccipital furrow. Facial suture, pre-ocular branch diverging outwards from eye, curving inwards at marginal furrow to cut a narrow strip from front edge of marginal rim laterally ; post-ocular branch diverging outwards but imperfectly known. Free cheek, thorax, pygidium unknown.

Remarks.—Despite the poor preservation, it is considered that these cranidia, which lack the pre-glabellar marginal indentation seen in *Pseudatops viola*, and possess palpebral lobes which are absent in that form, belong beyond the concept of the genus *Pseudatops*.

It must be recalled that the specimen figured by Lake (1931, pl. xvi, fig. 3) was the basis of his reference of all trilobites from the *Conocoryphe viola* beds to *Solenopleura*. It is readily granted that the limited available material here compared with *Protolenus howleyi* resembles *Solenopleura*. That species, originally found in the Lower Cambrian of Manuel's Brook, Newfoundland, was first named *Solenopleura* by Walcott (1889*a*) and in 1890 (p. 657) he added a query to the generic name but on the explanation of pl. xcvii this query was omitted.[1] The post-ocular branch of the facial suture appears to be shorter in the Penrhyn species than in *Solenopleura*, and Matthew (1899, p. 82) referred *S. howleyi* to *Protolenus*. R. and E. Richter (1941, p. 43 ; 1948, p. 27) do likewise, an opinion which we support if it is granted that *P. paradoxoides* Matthew is the genotype of *Protolenus*. Walcott (1890, p. 657) stated that in *S. howleyi* the surface is strongly granular or pustulose but the Penrhyn specimens do not

[1] Matthew, 1899, p. 82, draws attention to the misprint in Walcott's explanation of plate where the specific names *howleyi* and *harveyi* have been wrongly interchanged.

show this character. The pre-ocular branches of the facial sutures do not seem long enough nor divergent enough to refer the specimens to R. and E. Richter's genus *Lusatiops*.

6. Undetermined Trilobite

There are two cranidia, 19 and 30 mm. in length respectively, from the Green Slate of Penryhn, Sedg. Mus. 994*a*, *b* (counterparts) and E. B. Luxmoore Coll., Brit. Mus. (Nat. Hist.) In 37747, which resemble in some respects a cranidium from the Lower Cambrian of Comley, Shropshire, figured by Lake (1932, pl. xxi, fig. 7) as *Strenuella strenua* (Billings) and stated by him to resemble " the imperfectly known *S. strenuelloides* Cobbold ". The common features of the Welsh and Shropshire forms are the flat, sagittally long and arcuate anterior marginal rim and the slightly narrowing glabella. Both Penrhyn cranidia are larger than that from Comley and neither shows the palpebral ridge present in *Strenuella* ; in fact, both examples are badly preserved in the supposed palpebral region. Luxmoore's trilobite, however, possesses an " ocular " ridge on the front edge of the raised part of the left cheek.

It is possible that these cranidia are distorted forms of *P. viola* ; if so the long flat anterior marginal rim has resulted from compression accompanied by fracture or alternately it may represent a ventral preglabellar structure or doublure.

7. *Hyolithes* cf. *hathewayi* G. F. Matthew

Plate II, fig. 4

1899. *Hyolithes hathewayi* G. F. Matthew, *Trans. Roy. Soc. Canada*, [2], vol. v, sect. iv, p. 73, pl. iii, figs. 5*a–d*.

Material.—A unique slab in the Sedgwick Museum, A1171, collected by Robert Lloyd and presented by him in 1908, labelled " Tail of a trilobite ". The slab of Upper Green Slate shows trilobite fragments, including *Pseudatops viola* and three Hyolithids—the larger is compared with Matthew's species. This Hyolithid has been distorted by pressure but still retains some of its original convexity. One of the other two is probably conspecific with the larger.

Description.—Present length 60 mm., apical angle of divergence 40° narrowing to 20°.

Surface shows five growth striae near the aperture (four in 1 mm.), and along the shell various septa-like grooves which may represent growth thickenings. In the distal portion of the shell these are 2 mm. or 3 mm. apart.

At the aperture the shell is now 25 mm. in width.

From each side of the aperture protrude slightly curved and slightly

tapering structures, of which the left or better preserved is at least 37 mm. in length with a breadth of 3 mm. where it joins the shell ; its full extent is obscured since it reaches the margin of the slab, thus these would appear to have been at least two-thirds the length of the shell. The structure on the left side is frequently ridged perpendicular to its length ; this ridging is thought to be an accidental feature. It is unknown whether the structures were hollow or solid.

A smaller Hyolithid on the same slab is 18 mm. long and 5 mm. wide at its aperture, with an angle of divergence of 15° ; the shell shows a longitudinal furrow presumably the result of compression on an inflated surface ; the apertural margin is projecting on the supposed dorsal side.

No associated operculum known.

Remarks.—The large *Hyolithes* resembles *H. hathewayi* G. F. Matthew from the *Protolenus* Beds of Manuel's Brook, Newfoundland, in its size, apical angle, pattern of growth lines, and the transverse grooves ; it lacks, however, any longitudinal striae. If the change in convexity seen, about one-sixth of the length measuring from the aperture, means that this part of the shell has collapsed because the ventral margin of the aperture is at the change of convexity—then the dorsal lip is of such size as to compare with *H. princeps* Billings (Walcott, 1890, pl. lxxxvi) rather than with *H. hathewayi ; H. princeps* has been collected from the lower part of the *Protolenus* Beds at Manuel's Brook, Newfoundland, as well as at North Attleborough.

The systematic position of the Hyolithidae is obscure. The family was originally placed among the Pteropod mollusca by Nicholson, but Pelseneer (1888) in his study of the Pteropoda collected by the Challenger Expedition excluded Hyolithids from that group by " their triangular form, their partitions, and their operculum which in no respect resembles that of an operculate Mollusc ".

G. F. Matthew (1899*a*, p. 104) accepted this conclusion remarking on the absence of the molluscan protoconch in Hyolithids. He advocated placing the family in the Annelida close to *Serpula* and *Ditrupa*.

Grabau and Shimer (1909), however, placed Hyolithidae in the class Conularida within the phylum Mollusca stating " their relationship to the pteropods is probably distant, that of a parallel rather than a genetically related group ".

A new morphological feature became known when Walcott in 1911 (p. 121, pl. xix, fig. 7) illustrated from the Burgess Shale, near Field, British Columbia, *H. carinatus* Matthew " showing the triangular tube, operculum and, for the first time among the Hyolithidae the curved supports for the fins of a pteropod. The discovery of the animal that lived in one of the tubes that has been classed with the

pteropods removes one more doubtful form from the latter to the annelids and with it will probably go *Hyolithellus* and other tube-like shells that have none of the distinctive characters of *Hyolithes* and its allies". The quotation given was inserted into the observations following his description of the genotype of *Selkirkia*, a new genus of "Polychaetous annelids with a slender, straight, or slightly curved tube"; this form, he had previously described as *Orthotheca*, a genus usually considered as close to *Hyolithes*. Two other species, *S. fragilis* and *S. gracilis* were illustrated—these are both forms having thin conical tubes but to the writers their annelidan nature is doubtful. It seems clear, nevertheless, that Walcott when recording the finding of the "fins" in *Hyolithes* did not support the removal of the genus to the Annelida.

Since Walcott described the "curved supports for the fins" of the operculate Middle Cambrian *H. tricarinatus*, they have subsequently been described in other species, e.g. the Tremadoc *H. magnificus* Bulman (*in* Stubblefield and Bulman, 1927, p. 125, pl. iii, figs. 8, 14). The present Welsh form shows similar structures which, however, are relatively longer; this is perhaps logical in view of the larger shell. In all three cases the "fins" are narrow in comparison with the skeletally unsupported fins of living Pteropods and it may be significant that the well-preserved Burgess Shale *H. carinatus* shows no trace of any wider membrane or velum attached to the "fins" such as might assist in swimming. It is noteworthy, moreover, that paired structures with such skeletal supports appear to have no parallel either in Mollusca or Annelida.

Matthew (1899, p. 74) has suggested that *H. hathewayi* was a Hyolithid of a sedentary habit with the point of the tube fixed in the mud at the sea bottom. The presence of an operculum, of a shell frequently of triangular cross-section, and the occasional presence of shell-curvature which is usually concave on the keeled side of the Hyolithid favour a benthic and possibly sedentary habitat rather than a freely moving existence. In this case, the "fins" may have served a balancing function. It is unknown whether these structures could be retracted into the shell, but the Hyolithid operculum is typically without accommodating notches; its conical shape, however, is usually accompanied by flattened areas on the two symmetrical sides; whether these are merely for muscular attachments or whether they are related to the "fins" in any way is unknown. Novák (1891, pl. vi, figs. 6–12) gives figures of a Llanvirn species, *H. cinctus* Barrande, where on the inner side of the operculum there is a groove running along the symmetrical sides and two pits in the rounded angle between these sides. These grooves might possibly have lodged the proximal parts of the extended "fins" which could perhaps have been attached in

the pits. Somewhat similar structures are to be seen in the illustration of the operculum referred to the Middle Cambrian *H. tenuistriatus* Linnarsson by Holm (1893, pl. i, fig. 81). In describing the first recorded Hyolithid " fins " from the Lower Cambrian, the suggestion is made that the members of Walcott's Lower Cambrian genus *Helenia* may also be Hyolithid " fins ". These are flattened tubes described as open at both ends and as being calcareous. In certain species they show cancellate or granular ornament.

No observations are offered as to the nature of the original material of the Welsh Hyolithid shell, but many Hyolithid shells are known to be calcareous ; in the case of the thin-shelled shale-preserved forms this probably also holds true, but there is sometimes a doubt since shale-impressions are frequently all that survive of the shell.

Concerning the systematic position of the Hyolithidae, the writers offer support to the conclusions of one of the last palaeontologists to write on the subject, namely J. Brookes Knight, who in 1941 (p. 20) states that " Hyolithidae may be mollusks, but they are more likely representatives of some phylum otherwise unknown and now wholly extinct ; their resemblances to members of any living phyla are not impressive and may well be superficial ".

8. A Fragmentary Crustacean

1926. *Hyolithus* sp. Morris and Fearnsides, *Q.J.G.S.*, vol. lxxxii, p. 255.

In the G. J. Williams' collection in the National Museum of Wales, numbered 27.110.641 *a* and *b*, there is a fossil fragment preserved in counterpart in grey slate, found in October, 1905, in the Green Pit, Ty mawr Quarry, Nantlle. This fossil between 60 mm. and 70 mm. in length, is now interpreted as two abdominal joints of a fairly large crustacean. The distal segment is about 6 mm. in width terminally, widening to 17 mm. at its proximal end and in length it is some 35 mm. At the terminal end there appear to be two apophyses ; there is an oblique notching at the proximal end. The other segment is broken proximally where it is about 32 mm. wide, distally it is 22 mm.

The fossil is so fragmentary that it offers no contribution to the age of the containing beds.

9. Supposed Fossils from Horizons in the Llanberis Slate below the Upper Green Beds

McKenny Hughes (1889, p. 9) had recorded " traces of fossils " in the Old Blue Slate of the Sebastopol section of Penrhyn Quarry, 1,200 feet lower than " the zone of *C. viola* ". He considered these

as resembling " casts of the carapace of a Trilobite filled with radiating mineral matter ". Thanks to the kindness of the Curator of the Sedgwick Museum, Mr. A. G. Brighton, we have been permitted to borrow these specimens A 1168, A 1169, which occur in slate of a light green colour (Hughes, 1889, p. 11, stated that the colour was more green than blue) ; we consider them to show no organic structure. Dr. David Williams, to whom we submitted the slabs in 1938, reported : that the radiating brown material is mainly limonite-stained carbonates, and in the mass are many minute scalenohedra of calcite and occasional rhombs of calcite and possibly also of ankerite with traces of granular quartz ; the dark green material he determines as a chlorite (probably prochlorite) mixed with occasional flakes of sericite and idiomorphic crystals of apatite. The scalenohedra of calcite and idiomorphic apatite suggest to him an epigenetic origin.

In conclusion, we express our thanks to the authorities of the Bristol Museum and Art Gallery, the British Museum (Natural History), the Geological Survey Museum, the National Museum of Wales, the Sedgwick Museum, Cambridge, the Liverpool Museum, and the Imperial College of Science for lending us material for study ; also to the authorities of the American Museum of Natural History, the Royal Ontario Museum, Toronto, and the U.S. National Museum for kindly supplying photographs of specimens of *Atops* and *Pseudatops* in their collections.

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[1] According to Walcott, *Amer. Journ. Sci.*, (3), 37, 1889, p. 377, this was printed in 1886 but not distributed until 1887.

EXPLANATION OF PLATES

PLATE I

(Photographs natural size unless otherwise stated)

FIG. 1.—*Pseudatops viola* (H. Woodward) showing genal spines, and on right side cephalic articulation fulcrum, 17 thoracic segments and damaged pygidium. Upper Green Slate, Llanberis Slates, Penrhyn Quarries, Bethesda, Caernarvonshire. I. Griffiths Coll., Geol. Surv. Mus. 54912. Photo J. Rhodes.

FIG. 2.—*Pseudatops viola* internal mould portion of lectotype, showing three pairs of incised glabellar furrows, " ocular " ridge towards front of right cheek, course of marginal furrow on left. Horizon and locality as for fig. 1. Collected by R. E. Jones and R. Lloyd, University College Bangor Coll. on loan to Geological Survey Museum. Photo J. Rhodes.

FIG. 3.—*Atops trilineatus* Emmons, shale-preserved topotype figured by Walcott (1890, pl. xcv, fig. 5*a*), showing most of dorsal skeletal details except the course of the supposed " facial suture ". Lower Cambrian, roadside near the old Reynolds Inn, one mile west of North Greenwich, Washington County, New York. U.S. Nat. Mus. Washington, D.C., 171*y*. Photo C. E. Resser.

FIG. 4.—*Atops trilineatus* Emmons, holotype, horizon and locality as for fig. 3. Amer. Mus. Nat. Hist., New York. Photo, × 2, by Ben. F. Howell.

FIG. 5.—*Pseudatops viola* cephalon and part of thorax, compressed from back to front, horizon and locality as for figs. 1 and 2. E. B. Luxmoore Coll., Brit. Mus. (Nat. Hist.), In. 37746. Photo J. Rhodes.

PLATE II

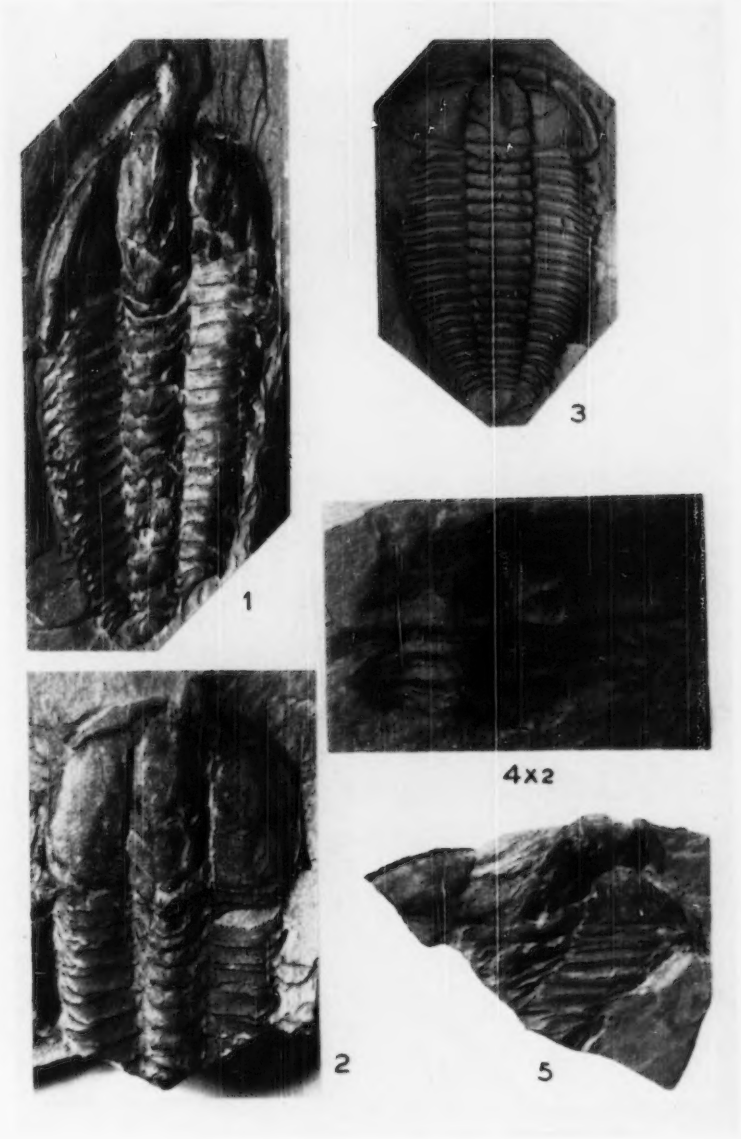
(Photographs natural size unless otherwise stated)

FIG. 1.—*Pseudatops reticulatus* (Walcott) var. *comleyensis* (Cobbold) cranidium figured by Cobbold (1936) and Lake (1940), showing " ocular " ridges and reticulate ornament. Lower Cambrian, *Eodiscus bellimarginatus* Limestone, Quarry Ridge, Comley, Shropshire. W. F. Whittard Coll., Geol. Surv. Mus. 53515. Photo, × 2, by E. S. Cobbold.

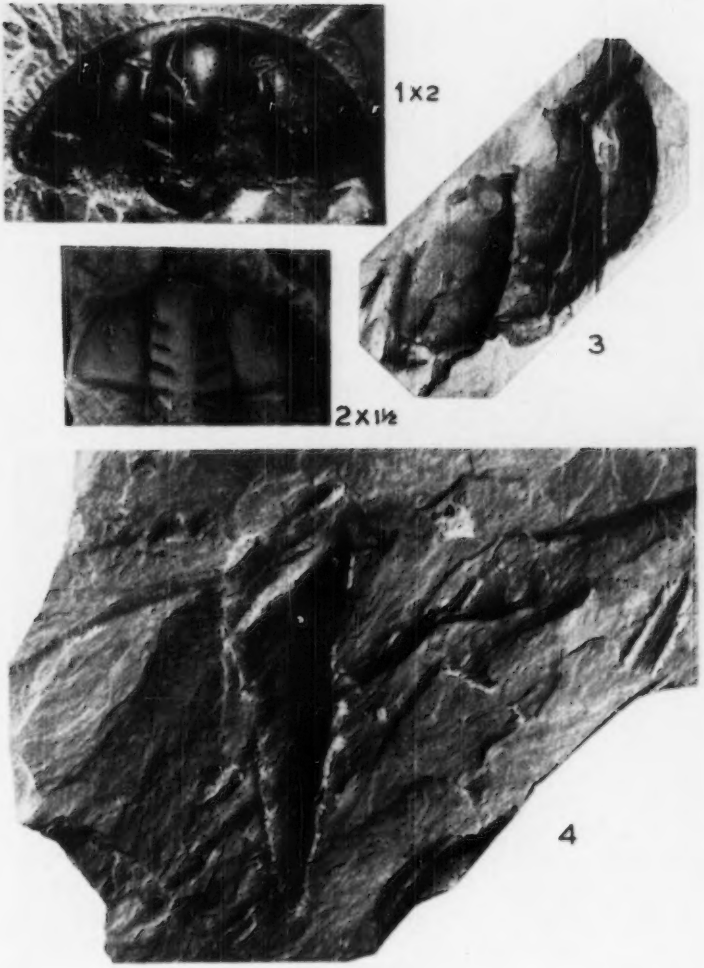
FIG. 2.—*Pseudatops reticulatus* (Walcott) holotype cranidium, preserved in limestone, figured Walcott, 1890, pl. xcv, fig. 6 ; note articulation fulcrum on right. Lower Cambrian, north-west side of Salem, Washington County, New York. U.S. Nat. Mus. 250*i*. Photo, × 1½, by C. E. Resser.

FIG. 3.—*Pseudatops viola* (H. Woodward), one of the original syntypes, a diagonally compressed specimen ; compare " ocular " ridge on right side with those shown in fig. 2. Horizon and locality as for Plate I, figs 1, 2, 5. Collected by J. J. Dobbie, Univ. Coll. Bangor Collection on loan to Geol. Surv. Mus. Photo J. Rhodes.

FIG. 4.—*Hyolithes* cf. *hathewayi* G. F. Matthew, large example showing paired outgrowths from the aperture. A second example is seen on the right-hand side. A fragment of *P. viola* is seen to right of apex of the larger Hyolithid. R. Lloyd Coll., Sedgwick Mus., Cambridge, A1171. Photo J. Rhodes.



PSEUDATOPS AND *ATOPS*.



PSEUDATOPS AND *HYOLITHES*.

A Note on Bathonian Gastropods Assigned to Freshwater Genera

By Hugh Watson

(PLATE III)

Abstract

It is claimed that the Bathonian gastropods recently assigned to *Bathonella* Yen do appear to not differ from *Viviparus* in any marked features of generic importance, and that there is really no satisfactory evidence to show that they and certain associated organisms lived in the sea rather than in fresh or brackish water.

In view of the correspondence in this magazine on "*Bathonella* and *Viviparus*" Dr. Arkell has asked me to make known my views on the question whether *Bathonella* Yen (1948) differs from *Viviparus* Montfort (1810) in conchological characters of generic importance and in having probably lived in the sea instead of in freshwater. It will be best to consider these two points separately.

Almost the only features which Dr. Yen (1948, p. 168) states characterize his proposed new genus, and which are not also to be found in typical species of *Viviparus*, are the naticoid form of the shell, implying that the spire is shorter than it usually is in *Viviparus*, and the descending body-whorl. But the height of the spire is a variable feature ; it is only short enough to make the shell naticoid in one of the four species and subspecies which Yen includes in his genus, namely *V. scoticus* (Tate) ; and even in this form it is no shorter than in the living American species, *V. intertextus* (Say). Similarly, the deflection of the last whorl is not a constant feature of the shells included by Yen in *Bathonella*, as may be seen from his own Plate XI, and it is also found in some living species of *Viviparus*, being conspicuous in the keeled form *V. museruensis* var. *pagodiformis* Smith (illustrated by Pilsbry and Bequaert, 1927, pl. xix, fig. 7).

Dr. Cox (1948, pp. 314, 315), however, mentions four other differences which he considers give to *Bathonella* an aspect unlike that of *Viviparus*.

In the first place, he says that *Bathonella* differs from *Viviparus* in having an acute projecting apex and an expanded, highly convex, last whorl, which make the shell elevated-turbinate rather than conical, a line tangential to the successive whorls presenting an outward-facing concavity in contrast to the corresponding convexity of *Viviparus*. But the well-known living species, usually called *V. fasciatus* (Müll.) in England and *V. viviparus* (Lin.) in Germany, has an acute projecting apex and very convex lower whorls, and a line tangential to the first three whorls is concave, although it becomes convex when tangential to the last three whorls. Thus, in the young of this recent species the turbinate form found in Yen's proposed new genus is well developed,

and it is not unusual for some of the early members of a genus to retain to maturity characters that are only found in the young of the more recently evolved species.

Secondly, he states that *Bathonella* differs from *Viviparus* in that the last whorl becomes almost detached from the parietal wall to which the continuous peristome adheres but loosely. Yen's photographic figures, however, show that this feature is not always very apparent in his new genus ; while in the recent species of *Viviparus* I have mentioned the lower whorls are separated by a very deep suture, and the practically continuous peristome is attached to the parietal wall for an unusually short distance, only about one-seventh of its circumference.

Thirdly, he states that while the aperture of *Viviparus* is " inverted-pyriform ", that of *Bathonella* is nearly semicircular, with the columellar lip (much straighter than in *Viviparus*) forming the diameter.[1] But in fully-grown specimens of this recent species of *Viviparus* the aperture is not inverted pyriform, but approximately ovate, as Yen describes and figures it in his proposed genus ; and the curvature of the columella also agrees closely with most of Yen's figures, being intermediate between that of the two type specimens of *Viviparus langtonensis* (Hudleston) belonging to the Sedgwick Museum, a form which Yen thinks may be only subspecifically distinct from *V. scoticus* (Tate), the type species of his new genus.

Lastly, Cox says that the test of *Bathonella* is thicker than that of *Viviparus*. But Yen writes of the " thin shell substance " of his new genus ; and the many species of *Viviparus* itself vary considerably in the thickness of their shells, the thickest forms having naturally had the best chance of being preserved as fossils.

Sometimes when the form of a shell shows little that is distinctive the microscopical sculpture is of greater systematic value, especially that of the apical whorls. This is seldom preserved in these fossils, but through the kindness of the Palaeontologist of the Geological Survey I have been able to examine forty-five specimens of *Viviparus langtonensis* (Hudleston), three of which show it. These have the same type of fine, threadlike, spiral striae on the upper whorls which also characterize the later species of *Viviparus*, both recent and fossil, and which gradually die out on the lower whorls, as in the typical members of the genus. The axial striae crossing them are usually stronger on the upper whorls than they are in the living British species, but their strength varies considerably in the different specimens (see the accompanying drawings) and is, on an average, scarcely greater than in one of the recent Indian species that I have examined.

[1] Anderson and Cox (1949, p. 177), however, now describe the aperture of *Bathonella* as circular.

Thus, *V. langtonensis* agrees with living members of the genus in the type of its microscopical sculpture.

In at least three of the forms that Yen places in *Bathonella*—*Viviparus langtonensis* (Hudleston) *V. scoticus* (Tate) and *V. aurelianus* Cossmann —the outer lip and the lines of growth on the last whorl curve backwards between the suture and the periphery and again on the base more markedly than they do in the typical species of *Viviparus*. But a similar curvature is found in the Purbeckian species *V. subangulatis* (Roemer) (see Arkell, 1941, p. 86, figs. 7*a* and *b*), and, in any case, the difference is not very great, and had it been at all constant it would doubtless have been mentioned by Dr. Cox. Indeed, that so able and experienced a palaeontologist should have discovered no more substantial and less inconstant differences between the shells of *Bathonella* and *Viviparus* than the four that he does mention strongly supports the view that none exist of generic importance. Hudleston (1896, p. 488), who uses the name *Paludina* for the genus we now call *Viviparus*, states that we cannot doubt that *P. scotica* Tate, which Yen makes the genotype of *Bathonella*, is correctly referred to the genus *Paludina* ; and he adds, on the next page, that *P. Langtonensis* differs but little from the existing species, *P. vivipara*. Similarly, Cossmann (1899, p. 142), when describing *V. aurelianus*, states that, apart from its more expanded last whorl, it is indisputable that this species presents all the characters of the genus *Viviparus*. Thus, any differences that separate the four species and subspecies which Yen places in *Bathonella* from the typical species of *Viviparus* appear to be much less striking than those that separate some of the groups of *Viviparus* that have merely been given subgeneric rank (see, for example, the figure of *V.* (*Eyriesia*) *eyriesi* (Morelet) given by Thiele in his well-known Handbuch, 1929, p. 114, fig. 86). Accordingly, the characters of the shell seem to afford little justification for placing in a separate genus from *Viviparus* the species that Yen assigns to *Bathonella*, and none for placing them in a separate family. And as not only *Viviparus* itself but practically all the known genera of the Viviparidae live in freshwater, it follows that these species probably did so too, unless there should be any other good evidence that they lived in the sea. If there had been any such evidence, then these species might have belonged to a marine family some members of which had developed almost exactly the same simple form of shell as we find in *Viviparus* ; or it might be that in Jurassic times, when the sea was slightly less salt than it now is, a few members of the Viviparidae were able to live therein. But it is difficult to find any good grounds for Yen's statement (1948, p. 169) that the evidence suggests that the species he places in *Bathonella* had a marine habitat.

The four species and subspecies that Yen assigns to his proposed new genus are all of Bathonian age. Two of them—*Viviparus scoticus*

(Tate, 1873) and *bithynoides* (Yen, 1948)—occur together in the Great Estuarine Series of the island of Skye, strata that seem to have been laid down under deltaic conditions which produce alternations of marine and freshwater deposits. According to Cox (1948, p. 314), "*Bathonella*" occurs at intermittent horizons through at least 100 feet of these Great Estuarine beds. In the exposure that Yen himself examined he states (1948, p. 167) that he found both species of "*Bathonella*" in a deposit of sandy limestone, associated with a pelecypod that he provisionally identified as *Cyrena* (= *Corbicula*) *jamesoni* Forbes, a species supposed to have lived in fresh or brackish water. Although its hinge-structure is unknown, Anderson and Cox (1949, pp. 109–111, 120) now include this form in *Protomiodon*, a genus they regard as ancestral to *Neomiodon*, so abundant in the brackish-water Purbeck and Wealden strata. On the other hand, in another bed, consisting of fine-grained cement stone, he found marine fossils, including two species of *Procerithium*; but he seems to have found no specimens of either species of "*Bathonella*" in this bed. Accordingly, the evidence recorded by Yen himself scarcely supports the view that *V. scoticus* and *bithynoides* are marine species.

Of the remaining two species or subspecies that Yen places in his new genus one is *Viviparus aurelianus*, described by Cossmann (1899, pp. 141, 565, pl. xvii, figs. 2–7), who stated that it occurs very abundantly in a freshwater deposit, ½ to 1½ metres in thickness, among the Bathonian strata exposed at St. Gaultier in the Department of Indre in Central France. Associated with *V. aurelianus* Cossmann stated that some remains of plants were to be found (1899, p. 139), and a few specimens of another freshwater snail, which he named *Valvata* (*Cincinna*) *benoisti* (pp. 142, 143, 566, pl. xvii, figs. 8, 9), a species not unlike a depressed form of the common recent species *V.* (*C.*) *piscinalis* (Müll.). But notwithstanding the abundance of marine gastropods, belonging to forty-four different species, that had been collected from the adjacent deposits at St. Gaultier, not one of them seems to have been found in the bed containing the numerous specimens of *Viviparus aurelianus* (p. 565), although it would not be surprising if a few examples derived from the adjacent beds had become mixed with them.[1] These facts led Cossmann to believe that before the *Viviparus* bed was deposited a slow uplift took place, the sea

[1] At the foot of Cossmann's page 565 there is an unfortunate error. It is there stated that *Viviparus aurelianus* is very abundant in "Calcaire No. 4"; but the figure "4" seems to be a misprint for "6", for Cossmann makes it quite clear that the bed in which *Viviparus aurelianus* is abundant, and in which *Valvata benoisti* also occurs, is the one that he numbers "6" elsewhere in this second paper (see pp. 543, 566, etc.). Perhaps this mistake is the source of Yen's statement that in Indre the genera *Nerinea*, *Delphinula*, *Emarginula*, and *Patella* are associated with "*Bathonella*" (1948, p. 169),

retreated a certain distance, and freshwater ponds or marshes were then formed in which *V. aurelianus* became established ; but that later a slight depression caused the sea to return and marine forms again to occupy the place where the *Viviparus* had lived. And if we were to reject this hypothesis and maintain that the conditions probably remained uniformally marine throughout, it would be very difficult to explain why this complete change in the character of the fossil fauna took place.

If a similar slight elevation occurred also in England, with the formation of freshwater marshes or lakes in the area from which the shallow sea had temporarily retreated, this would explain the facts concerning the remaining form that Yen assigned to his new genus, namely *Viviparus langtonensis* (Hudleston, 1896, pp. 488, 489, pl. xliv, figs. 1*a*, 1*b*). This species appears to have much in common with *V. aurelianus*, both forms being considered by Anderson and Cox (1949, pp. 115, 116) to be inseparable from *V. scoticus* (Tate). It occurs in a thin and patchy deposit of marl, with a pebble bed at its base, which rests somewhat unconformably on the Chipping Norton Limestone and Lower Sharp's Hill Beds of the Bathonian strata in North Oxfordshire (see Arkell, 1947, pp. 39, 63–5). According to Hudleston, other freshwater species and occasionally seeds of *Chara*, etc., are present in the same thin deposit in which *V. langtonensis* is common. The only one of these other freshwater forms, however, which he named and described is *Valvata comes* Hudleston (1896, p. 489, pl. xliii, fig. 27, and xliv, figs. 2*a*, 2*b*), a small species not very unlike the common Purbeckian species *V. helicoides* (Forbes MS.) de Loriol (see Arkell, 1941, p. 91, figs. 14*a* and *b*, p. 119, figs. 60–2), and resembling rather closely the type species of *Valvata*—*V. cristata* Müll.—except for its distinctly raised spire, a fact that I can confirm through having had the privilege of studying the type specimens of this species, as well as those of *Viviparus langtonensis* itself. Quite recently Sylvester Bradley (1948) has not only confirmed the presence in this Viviparus Marl of *Gyrogonites* belonging to the Charophyta, plants that never live in the sea, but has also found in it an undescribed species of the ostracod *Metacypris* which is similarly confined to fresh or only slightly brackish water ; and he adds that both Charophytes and *Metacypris* are abundant associates of *Viviparus* and *Valvata* in the Cherty Freshwater Beds of the Middle Purbeck of Dorset. Surely it is highly improbable

for Cossmann's bed " No. 4 " is that in which these and many other marine genera are found. Or possibly Yen used the term " associated " in a broad sense to include forms found in adjacent beds of the same series in the same locality, for he also stated that in Skye he had shown that " *Bathonella* " occurs with *Procerithium*, whereas what he showed was that it occurred in a neighbouring but distinct bed of a different lithological character. It need scarcely be emphasized that different beds may have been laid down under quite different conditions even when they are adjacent to each other.

that these diverse organisms found in this Bathonian deposit should not be what they appear to be, but should really be marine forms which had suddenly and simultaneously developed for a short time a deceptively close resemblance to freshwater forms differing widely from one another that also lived in the Jurassic period. It is true that a few marine gastropods have also been found in this Oxfordshire deposit ; but this is not surprising when we remember that the bed is stated to be usually not more than about 3 inches thick, and, where the marine fossils have been found, to rest directly on the highly fossiliferous marine strata of the Lower Sharp's Hill Beds, with a gentle unconformity between them. Thus, the marine forms in the Viviparus Marl may easily have been derived from the underlying marine strata, a view supported by the pebbles and phosphatic nodules that the Marl also contains.

Alternatively, it is possible that the Viviparus Marl of North Oxfordshire may have been formed by a large river, when abnormally flooded, having washed into the sea numerous freshwater shells which were deposited among marine forms beyond the river's mouth. This hypothesis, or one very similar to it, has the support of the eminent French geologist, Haug (1921), as well as of Dr. Arkell (1948), who has so carefully studied the Jurassic rocks of Oxfordshire and elsewhere, and to whom my thanks are due for much kind help. We know that non-marine shells are sometimes carried down into the sea, because they are occasionally found cast up with marine forms on the sea shore. We know, too, that great quantities of estuarine or freshwater Pectinibranchs may live in swamps near the mouths of rivers such as the Congo (see Pilsbry and Bequaert, 1927, pl. lxxvii) ; and after floods one often finds considerable accumulations of empty freshwater shells stranded on low ground by the sides of rivers. Moreover, members of the relatively primitive families Viviparidae and Valvatidae seem to have been specially common in the freshwaters of the Jurassic Period. Clearly, therefore, a quantity of such shells might be swept down into the sea by an exceptional flood, such as might occur if a natural dam holding back a lake in the river valley were to burst after torrential rain and lead to a great volume of water sweeping down the river and carrying with it to the sea all loose objects that lay in its course. Specimens that had dried and become filled with air, through having been stranded on the river banks after former minor floods, might float far out to sea, like the pieces of wood, etc., discharged by the Amazon in times of flood ; but they would become scattered before sinking and are very unlikely to form an appreciable element in any deposit laid down at a great distance from the coast. Moreover, the influence of the tides would tend to cause the majority of these shells to be drifted sideways over any low-lying ground when they approached

the river's mouth, whereas the slightly less buoyant specimens would be more likely to be swept straight forward into the sea during such an exceptional flood. They would probably come to rest, however, as soon as the current slackened within a few miles of the mouth of the river, and might there form, with other debris from the flood, a thin patchy deposit of limited extent, distinguishable from the adjacent beds by containing freshwater as well as marine shells. The Viviparus Marl of North Oxfordshire seems to be a thin deposit not unlike this ; so far as I know it does not extend far ; and the evidence of the remains of land animals and plants mixed with marine fossils in the neighbouring and practically contemporaneous Stonesfield Slates suggests that land was not far away, from which a large river may have issued. The unconformity at the base of the Viviparus Marl might easily have been caused by submarine erosion due to the currents produced by the first onrush of the flooded river into the sea.

On the other hand, this unconformity could also be easily explained if we accept the view that this Oxfordshire deposit was probably formed in the same way as Cossmann believed the somewhat thicker one in Central France had been formed, that is to say, by the slight elevation of a tract of land that had been covered by the sea, and the formation thereon of freshwater marshes or lakes, in which the *Viviparus* and the associated non-marine species flourished until the sea again flowed over the area. In this case some erosion would almost certainly occur during or immediately after the raising of the land above sea-level before the marshes or lakes were established, thus producing the unconformity. And in favour of this hypothesis it may be added that, while a river flood great enough to sweep into the sea a sufficient number of freshwater shells to form even a thin deposit must have been a very rare event, the extent, thickness, and character of the various deposits of Bathonian age in Southern England show so much diversity that it is very unlikely that the exact limits of the area occupied by the shallow Bathonian sea did not fluctuate.

But which of these two views about the formation of the Viviparus Marl of North Oxfordshire is the more probable is a stratigraphical problem to be solved by the student of palaeogeography rather than of palaeozoology. Suffice it to say that either of these two hypotheses seems to be far more likely than the one favoured by Prashad (1928), Yen (1948), and Cox (1948), which appears to imply that the various Bathonian species found in Skye, Oxfordshire, and Central France that have been assigned to the genera *Viviparus*, *Valvata*, *Corbicula*, *Metacypris*, and *Chara* (or some allied genus of plants) do not really belong to these freshwater genera—which are known to have been common in Jurassic times—but are marine forms which, by an extraordinary coincidence, had simultaneously come to resemble these

different freshwater forms very closely indeed. Surely, to accept this view is to stretch the long arm of coincidence too far !

And it would be no less improbable if it were supposed that the gastropods just mentioned were marine forms, while the rest, such as *Metacypris*, lived in freshwater, but had been brought down into the sea either by a flooded river or by the slight subsidence of the area in which they had become established when the sea had temporarily receded from it. Seeing that in the fresh or only slightly brackish waters of later Jurassic times *Metacypris* was associated with abundant specimens of both *Viviparus* and *Valvata*, it would be strange indeed if not only did neither of these genera of freshwater gastropods accompany this ostracod in the Bathonian deposits, but that their places were there taken by members of different marine families which had happened to have come to simulate these particular freshwater genera so closely that able palaeontologists, both in England and in France, have independently concluded that they undoubtedly belonged to them.[1] By convergent evolution gastropods belonging to different groups have sometimes come to resemble each other very closely in their external appearance when they are adapted to living in the same type of environment ; but when one is adapted to marine conditions and another to a freshwater habitat the resemblance is seldom close enough to mislead an experienced conchologist unless the specimens are in very poor condition. Let us hope, therefore, that palaeontologists will refrain from assuming that good authorities like Hudleston, Cossmann, and others have all been deceived, and from removing to marine families the Bathonian species we have been considering, until we have far more satisfactory evidence that they do not belong to the freshwater genera they so much resemble, but that they actually did inhabit the sea.[2]

[1] Anderson and Cox (1949, p. 116) claim that because Phillips in 1871 (p. 181, pl. x, fig. 34), when he figured the form that Hudleston named *Paludina langtonensis* twenty-five years afterwards, called this species *Phasianella elegans*, he " regarded it as probably marine " ; but Dr. Arkell thinks that this is more likely to have been a misidentification with the *Phasianella elegans* of Morris and Lycett, to whom Phillips attributes this name on p. 243.

[2] It has been suggested that, as the affinities of the Bathonian gastropods that have been assigned to *Viviparus* and *Valvata* are not certain, but are subject to differences of opinion, these species should be placed separately under the heading " *incertae sedes* ". To adopt this course, however, would be misleading, as it would imply that the relationships of these forms are even more doubtful than those of numerous other fossil gastropods which are not usually placed in this category, although their affinities are at least as debatable and often far more so. It would seem better to follow those writers who retain species in the genera and families in which they have usually been placed—merely adding a question mark to the names of any of which the affinities are exceptionally problematical—until good evidence, which will bear critical examination, has been brought forward to show that they more probably belong to other groups.

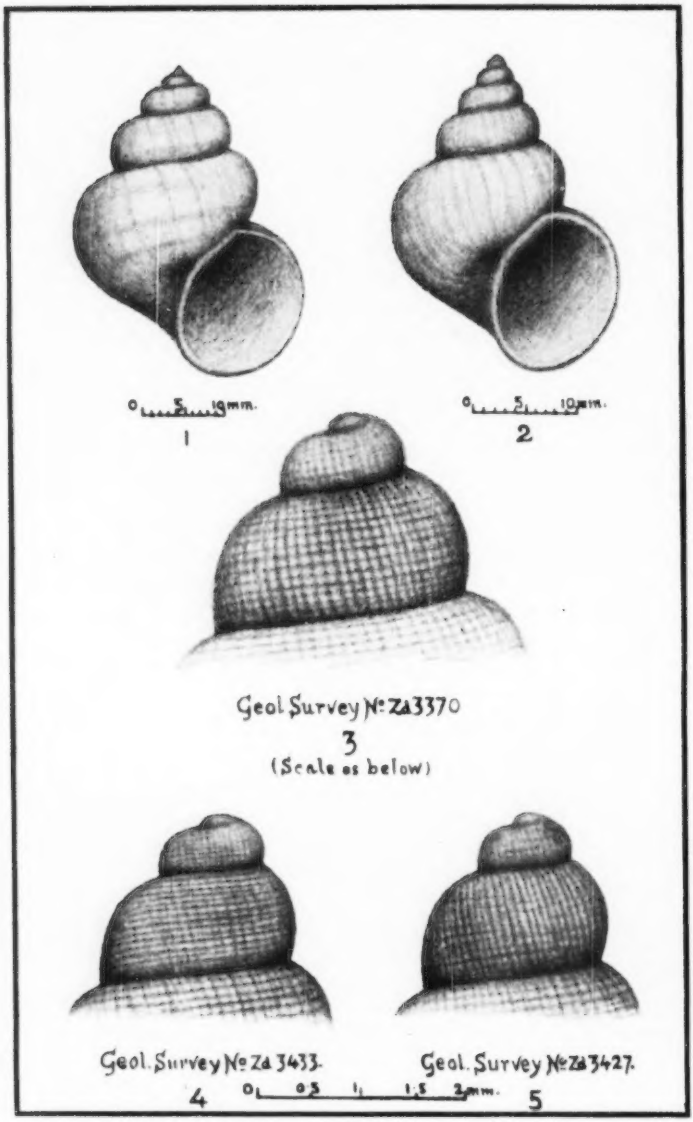


Fig. 1, a recent, and Figs. 2–5, a Bathonian, *Viviparus*.

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EXPLANATION OF PLATE

FIG. 1.—Shell of the common recent species of *Viviparus*, *V. fasciatus* (Müll.), for comparison with that of the Bathonian form, *V. langtonensis* (Hudl.). Drawn from a specimen collected by the author in Coe Fen, Cambridge. × 1·2.

FIG. 2.—Shell of *Viviparus langtonensis* (Hudl.) from the Viviparus Marl of the Bathonian beds of North Oxfordshire. Drawn from specimens belonging to the Geological Survey, from Sharp's Hill, near Hook Norton, and Castle Barn Quarry, near Chipping Norton. × 1·5. The shell of the genotype of *Bathonella*, *V. scoticus* (Tate)—of which *V. langtonensis* may be only a subspecies—is similar, but relatively shorter, with a broader last whorl and aperture, having thus the more turbinate form characteristic of young specimens of *V. fasciatus*.

FIG. 3.—Upper whorls of *Viviparus langtonensis* (Hudl.) from the Viviparus Marl of the Bathonian beds of North Oxfordshire, showing the microscopical sculpture. Drawn from a specimen belonging to the Geological Survey, from Sharp's Hill, near Hook Norton. × 15.

FIGS. 4 AND 5.—Upper whorls of *Viviparus langtonensis* (Hudl.) from the Viviparus Marl of the Bathonian beds in another locality in North Oxfordshire, showing that in this species the microscopical sculpture varies, even in specimens found together, in the same way as it does among different recent species of *Viviparus*. Drawn from specimens belonging to the Geological Survey, from Castle Barn Quarry, near Chipping Norton. × 15.

Note.—The drawings of the fossil shells are semi-diagrammatic, defects in the original specimens not being shown.

The Influence of Water Films adsorbed by Mineral Grains upon the Compaction of Natural Sediments and Notes on Allied Phenomena.

By W. Sugden

Abstract

The mechanism of the compaction of sediments is discussed, with special reference to the rôle played by adsorbed water, under both normal conditions and conditions of erosion and tectonic force. The effect of adsorbed water on the migration of oil and gas, and the possible relation of sediment-compaction to submarine slumping and sedimentary volcanism are also reviewed.

I. Introduction

SINCE the early days of geological science there has been a great deal of interest in the manner in which highly porous sediments pass through various stages of natural consolidation and compaction. Part of this process takes place as the result of the compression of older sediments by those later deposited, and it is this stage which has been of particular interest to the author. The theoretical and practical studies of other authors have led to many useful qualitative statements, and there has been some attempt at quantitative speculation. By this means certain basic principles have been established, and these principles are valuable as a guide to further thought, but final conclusions have not yet been reached on many points. This must be so, since we are yet far from a complete understanding of the highly complex nature of sediments, the system with which we are dealing, and it is unlikely that there will be anything approaching a proper understanding until much more research work has been done.

Continual advancement is, however, being achieved, and from time to time further contributions can be made which result in a somewhat more comprehensive theory of the mechanisms involved. The object of the present paper is to make some small contribution by discussing the possible importance of the adsorption of water by mineral grains. The study of the adsorption of water by mineral grains has so far been almost the prerogative of ceramic physicists and chemists, and their researches are now so far advanced that their findings become of interest and importance when considering the compaction of sediments.

II. The Mechanism of Normal Sedimentary Compaction

The main principle of the compaction of sediments is relatively simple. As a sediment is deposited its porosity may be very high, and in many cases the volume of pore space will be greater than the total

volume of hard grains. As the sediment becomes subject to the increasing load of superincumbent sediments, water will be expelled from it and the pore space will be reduced, the reduction depending on the applied pressure and the nature of the sediment.

Further inquiry immediately reveals complications, and the simplest way to approach the subject is to consider first of all the case of an ideal fine-grained sediment. Let it be assumed that in this sediment all the pore spaces are freely connected to one another and are entirely filled with water, and that there is no chemical or chemico-physical relationship between the interstitial water and the grains. If no external pressure is applied to such a sediment the water will be under hydrostatic pressure only, which will be dependent on the density of the water. This pressure will be transmitted by the water to the surface of the grains. The grains themselves will have a certain effective weight, dependent on the difference between their own density and the density of the water. This effective weight will be transmitted from grain to grain through their points of contact, and will be cumulative going downwards in the sediment. Such a pressure, active only between the points of contact of the grains may be called the intergranular pressure.

At any point in such a sediment the intergranular pressure will be

$$x(1 - p)\ (d' - d)$$

where x is the depth of that point in the sediment, p is the average porosity above that point expressed as a simple fraction, d' is the average density of the grains, and d is the density of the water.

Let us now imagine an impermeable tube, closed at the lower end with impermeable material, and filled with such an ideal sediment, the open end being occupied by a highly permeable piston which rests on the sediment. If pressure is suddenly applied to the piston any additional pressure on the sediment will be momentarily transmitted throughout the sediment as an even increase in intergranular pressure and an even increase in pressure within the water, the increases in pressure being dependent on the relative compressibility of the water and the grains. If the external pressure is maintained, the additional pressure within the water will then decrease as a certain volume of water passes into the piston, the rate of decrease depending on the permeability of the sediment and the viscosity of the water. Eventually the whole of the pressure applied to the piston will be taken up by the grains alone, and at such a time the pressure within the water will have returned to hydrostatic value.

While these changes in pressure are taking place there may be some compaction of the sediment by reorientation or change in shape of the grains. Until equilibrium conditions are again achieved fluid pressure will be in excess of hydrostatic pressure, and that part of the fluid

pressure which is in excess of hydrostatic pressure may be conveniently termed hydrodynamic pressure, since it is this pressure which is immediately responsible for the expulsion of water from the sediment.

The conditions obtaining immediately after pressure has been applied to the piston are partly analagous to the conditions which occur in a column of natural sediments in a state of partial compaction, but the above theoretical conception cannot be strictly applied owing to the adsorption of water at the surface of mineral grains. Hobson (1943) makes a cursory reference to this fact, but does not go deeply into its implications. After considerable research into the adsorption of water at the surface of mineral grains there is still some difference of opinion between various authors as to the exact nature of the causes of adsorption and the physical nature of the adsorbed water (Williamson, 1948). It is, however, an accepted fact that there is at the surface of mineral grains a thin film of adsorbed water which may be held to the grains with considerable force. Attempts have been made to measure the thickness of the adsorbed films (Hobson, 1943, Williamson, 1948, Bancroft, 1932), but apart from demonstrating that these may be many molecules in thickness there is available little reliable and precise information. Nevertheless, it is soundly established that the film thickness depends on a number of variable conditions. The most important of these are enumerated below.

(1) The film thickness depends on the elements exposed at the surface of a grain and on the structural arrangement of the atoms of these elements within the grains, each mineral having a different adsorptive power and consequently a different film thickness (Williamson, 1948). It is also to be expected that different surfaces of the same grain will have different adsorptive power, according to the structure exposed.

(2) Temperature affects the film thickness, an increase in temperature decreasing the thickness of the film.

(3) Increasing pressure reduces the film thickness. The converse is also true, but there would seem to be some hysteresis in the building up of films after the release of pressure. According to Williamson (op. cit.) there is an equilibrium film thickness at any particular pressure. The films will attain this equilibrium thickness if sufficient time is permitted.

(4) The film thickness varies with the concentration of substances in solution in the surrounding free water (Williamson, op. cit.). The relative concentration of dissociated ions would appear to be the conditioning factor in this instance, though undissociated substances may have a considerable effect. Minerals, in addition to their power of adsorbing water, are also able to adsorb ions selectively from the surrounding solution, the ions adsorbed depending on the relative concentration of the various ions in the solution, and upon the

particular mineral concerned. The water film thickness around the grains is affected by the adsorption of different ions by the mineral.

Since very little is known of actual film thicknesses it is impossible to give more than a rough comparison of the thicknesses of the adsorbed films of different minerals. The base exchange clay minerals, in addition to being able to adsorb water externally, are able to accommodate various volumes of water within the mineral layer lattice, and it has been shown that the volume of water internally or externally housed depends on the bases present within the mineral (Williamson, op. cit.). There would appear to be no other group of minerals with an adsorptive power approaching that of certain chemico-physical states of the base exchange minerals.

It will be seen from the above that a natural sediment is not merely a mass of grains with normal fluid water in the interstices, but is a highly complicated system, which is very liable to variation. When we consider the expulsion of water which takes place during compaction this highly complex system should be taken into account. The simplest conception relevant to the present discussion, and which approaches the full truth, is of a system of three parts.

(1) Hard mineral grains.

(2) Free water in a normal fluid state with dissolved salts.

(3) Quasi-rigid adsorbed films surrounding the grains and attached to the grains with a varying degree of constraint.

Any normal thick column of sediments will consist of alternations of coarser- and finer-grained sediments. At the time of deposition a coarse-grained sediment will have greater permeability but lower porosity than its finer-grained equivalents. In such a coarse sediment the volume of adsorbed film water will be very small compared with the total volume of grains or pore space, and it will have little effect on the permeability. It will also give little interference with the spacing of the grains, and these may be regarded as virtually touching one another. A fine-grained sediment with a good proportion of very fine clay-sized grains will, on the other hand, normally consist, at the time of sedimentation, of a large number of flocculated or partly flocculated grains. Flocculation is still not fully understood (Bancroft, 1932, Searle, 1933), but it is obvious from the porosity of many fine-grained sediments that the structure of such sediments must be extremely open. Some of the grains may be in intimate contact with one another, but it may be deduced from the very high porosity that the majority of the grains cannot be in full contact with most of their neighbours, and it seems reasonable to suppose that the separation is caused by the presence of adsorbed water films.

After sedimentation has ceased, and without the application of

external pressure, a fine-grained sediment may somewhat reduce its own bulk, and at the same time build up a considerable gel strength. It seems probable that this is due to the reorientation of the grains, so as to give better cancellation of ionic charges which still remain after sedimentation has ceased. The grains are thus brought closer to one another, and may then be considered as forming themselves into a rough mesh or lattice work. Even after the compaction brought about during the formation of a gel, the volume of water in a sediment may be far greater than the volume of the grains.

An adsorbed water film is probably under greater pressure than the pressure of the normal fluid water surrounding it (Williamson, op. cit.), but this excess pressure tends to retain the water within the sediment, while hydrodynamic pressure, as previously defined, is the pressure which tends to expel it. Thus, the simple definition of hydrodynamic pressure in the case of an ideal sediment, which was given above, must be amplified. To give a working definition, which can be applied to a normal sediment, hydrodynamic pressure must be defined as the fluid pressure in excess of normal hydrostatic pressure within a sediment, which has been induced in the normally fluid water in that sediment as the result of the external compression of the whole of the bulk of the sediment. A practical definition of intergranular pressure may also be given, this being redefined as the pressure active between the points of contact of the grains of a sediment, or between the points of contact of the adsorbed water films surrounding the grains. For the purpose of the present discussion, the intergranular pressure must be taken to exclude attractive or repulsive forces between grains which are the result of ionic or atomic structural forces.

An equation was given above for the calculation of intergranular pressure in an ideal sediment in which the fluid pressure is equal to hydrostatic pressure throughout. This equation may also be applied to a normal sediment if the practical definition of intergranular pressure is accepted. In a column of sediments which are in a partial state of compaction, and in which hydrodynamic pressure is still active, this equation will become

$$Hp + Ip = x(1 - p)\ (d' - d)$$

where Hp is the hydrodynamic pressure and Ip is the intergranular pressure.

On the application of a sedimentary load to a fine-grained sediment the increasing pressure will reduce the equilibrium film thickness of the adsorbed water films, and at the same time cause hydrodynamic pressure to become active. Water will pass out of the sediment, and the sediment will tend to occupy a smaller equilibrium volume, at which no hydrodynamic pressure is active, and at which adsorbed

films of smaller equilibrium thickness surround the grains. On the application of pressure the permeability will at first increase, due to the reduction in volume of the adsorbed water. If sufficient pressure is applied rapidly enough to a very porous sediment, its internal structure may be partly destroyed, causing the sediment to become more or less fluid. In most normal cases of compaction the pressure is increased so slowly that a tendency of the sediment to become fluid is offset by the outflow of water, and there is no sudden destruction of the structure of the sediment. As water flows out of the sediment the permeability will be reduced by the closer approach of the grains and their quasi-rigid adsorbed water films.

As hydrodynamic pressure is induced in a sediment and water begins to pass out of it a hydrodynamic pressure gradient will be set up. For a given rate of flow the pressure gradient necessary to produce that flow will depend on the permeability of the sediment and the viscosity of the water. Thus, if water is passing at right-angles to the bedding of coarse and fine sediments, there will be a high pressure drop across the fine sediments and a low pressure drop across the coarse sediments. The expelled water will seek the easiest path of escape. If all the beds are continuous and horizontal the escape will be vertically upwards through coarse and fine sediments, but if the beds are dipping, the comparatively low pressure gradient along the length of the more permeable beds will normally facilitate the passage of water along them, and its more rapid escape from their upper ends. In this case, the flow from fine-grained beds may be at first downwards into coarse-grained beds and thence upwards through the coarse-grained beds towards the surface. A proof of this is given by Hobson (1943), who discussed the anomalous conditions which may result in such cases.

Although adsorbed water films may be considered as being in some respects semi-rigid, their compressive strength will be very low compared with that of solid mineral grains, this being especially so in the case of the outer part of the films which are not so rigidly held (Williamson, op. cit.). On account of this and on account of the open arrangement of the grains in a newly deposited fine-grained sediment, fine-grained sediments will at first be far more easily compacted than coarse-grained sediments. Eventually a point will be reached at which the intergranular pressure has virtually eliminated the water films at the points of contact of the grains. After such a pressure has been reached the relative reductions in volume of coarse and fine sediments will probably be very nearly equal. Finally, at high pressures, it is probable that adsorbed water will be almost completely eliminated ; especially as an increase in temperature is to be expected with increased depth of burial, and increasing temperature will contribute to the reduction of the water films.

There is at present no means of ascertaining the order of pressures at which these various stages will be operative. It may be that adsorbed water has an important effect in resisting compaction only at the comparatively low pressures of the early stages of compaction, but that it will have an effect is certain. Experimental and theoretical attempts have been made to find some definite relationship between the porosity of a compacted sediment and the pressure which has been applied to it. Hobson (1943) quotes some highly complex equations, the validity of which has been partially tested, but these equations cannot possibly cover all the variables operative during compaction and, as pointed out by Hobson, they can at best only lead to certain qualitative conclusions, most of which can be arrived at without recourse to mathematics.

The simplest relationship stated seems to be that given by Skempton (1944), and was formulated as the result of experiments with natural sediments. He states that if for a given sediment the voids ratio is plotted against the logarithm of the pressure, the curve obtained will approximate to a straight line. He also states that the gradient of this line will depend on the chemical and physical properties of the sediment. This relationship would appear to hold good over reasonable ranges of pressure if the sediment is allowed sufficient time to reach equilibrium volume.

In addition to uncertainty as to the nature of the variation of equilibrium volume with pressure, there is even greater uncertainty as to the time required for a compacting series to reach equilibrium volume. Hobson (op. cit.) points out that various writers assume that equilibrium conditions are reached " soon " geologically, or deduce that many millions of years will be required for a thick series even to approach equilibrium. The most important factors directly affecting the rate of outflow, and therefore the time required to reach equilibrium, are permeability, thickness, pressure, temperature, and viscosity. It is interesting to note that the effects of these factors are to a large extent interrelated, and also depend on many secondary conditions.

A full discussion of all the conditions affecting the rate of outflow is beyond the scope of the present paper, but one or two important points may be noted.

Hobson (op. cit.) deduces that after sedimentation ceases the hydrodynamic pressure at a given point and porosity at that point decrease with time, comparatively rapidly at first, and then more and more slowly. This statement receives experimental confirmation from the work of Skempton. Skempton (op. cit.) found, in his experiments with loaded samples of fine-grained sediments of 2 cm. thickness, that equilibrium conditions were reached after an interval of about twenty-four hours, the rate of consolidation decreasing with time. The samples thus investigated were of very porous sediments, and it is

improbable that equilibrium would be reached as rapidly in a well compacted sediment. It would seem, however, from other statements which Skempton makes, that he assumes that a normal compacting series will reach equilibrium in a short time geologically.

Skempton's experiments, and most other experiments involving the permeability of fine-grained sediments, have been carried out at pressures far below those which may become operative in a thick compacting series, and there seems to be a general assumption that the permeability of a fine-grained sediment at low fluid pressures is readily comparable with its permeability at high pressures. In this connection, mention should be made of the importance of the part which adsorbed water may play in varying the permeability of a sediment. It was suggested above that the permeability of a fine-grained sediment will depend to some extent on the pressure applied to it, and where high fluid pressures are involved their effect will be to increase the permeability. It has also been mentioned that increasing temperature with increasing depth of burial will assist in the reduction of water films, and will therefore also increase the permeability. At higher pressures the rate of expulsion of water will be in excess of what is to be deduced from low pressure experiments on permeability.

To what extent the rate of expulsion of water will be affected, it is at present impossible to predict, but the effect may be of great importance, and allowance should be made for it when making statements on rates of decay of pressure.

III. The Effect of Erosion and Tectonic Forces upon the Adsorption of Water

If a column of sediments becomes subjected to sub-aerial or submarine erosion, such erosion will tend to reduce dynamic fluid forces within the sediments. If hydrodynamic pressure is active at any point, a sufficient removal of overburden will reduce such pressure to zero, and there will be a corresponding increase in adsorbed water film thickness at that point. Similarly, if the external or internal hydrostatic head at any point becomes reduced during erosion such reduction will also result in a build up of film thickness, and it is theoretically possible that in a well compacted fine-grained sediment there may be such a build up of adsorbed water films that the pore spaces are virtually plugged, the sediment thus becoming impermeable. The removal of overburden will decrease intergranular pressure.

It might be expected that reduction of pressures below compaction equilibrium point would result in a tendency of the sediment to reabsorb water and increase its external volume, but there is every indication that if such a tendency exists it is normally nullified by other

forces, which maintain the sediment at its original compaction equilibrium volume. There is no evidence that large-scale swelling and absorption of water can take place in sediments in which pressure has been reduced, except in cases where there is a change in the chemical content of the contained water. It is at present difficult to make further speculations on this particular point.

If a sediment, stabilized in the above manner, becomes subjected to tectonic forces, and there is sufficient tectonic pressure to exceed the original compaction equilibrium pressure, conditions very similar to those occurring during normal sedimentary compaction will be reproduced, and there will be a similar expulsion of water.

IV. The Effect of Adsorbed Water upon the Migration of Oil and Gas

Some short comments may be made on the possible influence of adsorbed water films upon the migration of petroleum. The theory of the migration of globules of oil and gas through comparatively coarse-grained sediments has already been the subject of much research. It would seem to be a commonly accepted fact that in a natural coarse-grained sediment oil and gas will migrate in the form of globules, the size of the migrating globules tending to exceed the minimum pore sizes, so that there can be migration only under the influence of dynamic pressure gradients. It has been suggested by Illing (1938), who seems to assume that the same principles apply during the primary migration of oil or gas from a source rock to a reservoir rock, that the most suitable conditions for such migration occur during the early stages of the compaction of a sediment.

Accepting the condition that petroleum migrates as globules which approach or exceed the minimum pore size, the latter will have a great influence on primary migration. As has already been explained in the present paper, it is possible that the thickness of adsorbed water films may have a considerable influence on the effective pore size and permeability of a fine-grained sediment. It has also been pointed out that the thickness of adsorbed water films depends on the fluid pressure and temperature, and the migration of immiscible fluids through a fine-grained sediment may, therefore, be greatly influenced by variations of fluid pressure and temperature. The adsorbed film thickness will be most easily affected by pressure when the sediment is not much compacted, and thus there is some confirmatory theoretical evidence in favour of Illing's contention that the most suitable time for hydrocarbon migration is during the early stages of compaction. It has also been stated in the present paper that tectonic forces may produce the same effects within a sediment as simple sedimentary compacting forces, and

it is thus possible to revive fluid migration at some time during the history of a sediment without the application of additional sedimentary load. When considering the oil prospects of a series of sediments, their tectonic history should be considered in this light, and not only from the point of view of the formation of suitable structures and the possibility of the escape of petroleum.

It has already been explained that it is theoretically possible that on the release of pressure during erosion the corresponding thickening of adsorbed water films in a fine-grained sediment may entirely inhibit further fluid movements through that sediment. The efficiency of many fine-grained cap rocks may be due to this cause.

An interesting fact has been noted by Williamson which would seem to have some bearing on the origin and primary migration of petroleum. There is evidence that mineral grains, in addition to being able to adsorb water, are also able to adsorb certain organic compounds (Williamson, op. cit.). Unfortunately, there has been little investigation of this fact, but it would seem possible that more extensive work on these lines would do something to unravel some of the mysteries of origin and primary migration.

V. Submarine Slumping

Submarine slumping is a phenomenon which is known to be by no means uncommon, and many fossil submarine slumps have been described. In spite of this, the writer has found no fully satisfactory explanation of the mechanism of such slumping. There is no complete analogy between sub-aerial landslides, the mechanism of which is understood, and submarine slumps. The vast majority of submarine slumps occur in sediments which have been recently deposited, and particularly in sediments which must be supposed to have been rapidly deposited. It is known that such slumps can take place on slopes of very low angle, far less than the normal critical angle of rest in water of the sediments involved, and slumping at low angles would appear to be the rule rather than the exception. As an instance of the low angles at which slumps can take place, Heim gives an example of a slump in a Swiss lake, the average angle at which the slide took place being 2° 31′. To properly explain the mechanism of submarine slumping it is necessary to give reasons firstly why submarine slumping is common only when penecontemporaneous with sedimentation, and secondly, why slumping can take place at gradients far less than the usual critical angle of slope of the sediments.

Jones (1944) discusses the mechanism operative during slumping, and stresses the importance of a fact investigated by Skempton. Skempton (op. cit.) states that a naturally compacted clay has a greater voids ratio than a sample of the same clay which has been made into a slurry

and compacted to the same pressure in the laboratory. He calculated that slurrying and reconsolidation of a clay might result in a difference in the voids ratio of 20 per cent, and be accompanied by a drop in strength which might be as much as 70–80 per cent. These changes Skempton attributes to the fact that in a natural clay the grains are held together by bonds of a chemico-physical nature, the intergranular structure being extremely open. There is support for Skempton's views in the well-known gelling characteristics of rotary drilling muds. Laying stress on this particular phenomenon, Jones (op. cit.) states that in a body of sediments with a tendency to slump, shear forces will bring about a rupture at a surface lying at some depth in the sediments, and the rupture will then extend laterally and upwards, to emerge on the floor of the sea. The breakdown of the structure of the sediment will take place first at the shear surface, and the resultant discharge of water will liquify the sediment near the shear surface and thus greatly lower its resistance to shear forces.

This explanation of the mechanism of slumping is applicable to certain types of slump which are described in various papers and which the writer himself has observed. These are of common occurrence and produce a type of structure which may be compared with that of a sandwich made up of deposits which have been completely slurried between two layers of normal sediments, these having suffered little disturbance, except to be moved almost parallel to one another. In many such cases there is no doubt that at the time of slumping the middle disturbed layer was reduced to a very liquid state. In many observed cases, however, there is very little definite evidence of liquefaction of any of the sediments concerned, although there may be abundant evidence that parts of the sediment were in a very plastic state at the time of slumping. Moreover, Jones' theory gives no indication of a reason why slumps can be initiated on very low angle slopes.

Regarding rather more compact sediments which cannot be easily slurried, Williamson (op. cit.) makes an interesting reference to the work of Grim and Rowland. When experimenting with moist clays, they found that in endeavouring to force such a clay through an orifice there was a sudden transition from impossibility to easy extrusion, as the water content was raised by a small critical increment. Williamson states that this increment would appear to be that necessary to increase the initially rigid adsorbed water films until a measure of mobility is possible. From this statement it would seem possible to make the assumption that for a fine-grained sediment with a fairly high voids ratio there will be, for any particular water content, a critical pressure, above which the sediment will rapidly lose its internal cohesion and above which its internal strength will be suddenly reduced. This critical pressure would probably be found to coincide with the

compaction equilibrium pressure, though there is at present no proof of this. Thus, the experiments of Grim and Rowland would seem to give practical confirmation to the theoretical statements previously made that when equilibrium compaction pressure is exceeded the internal structure of a sediment will become partly destroyed, but that the total breakdown of the structure will not necessarily take place.

During the deposition of sediments, compaction equilibrium pressures must be exceeded, the degree to which they are exceeded depending on a number of variables, including the nature of the sediments and the rate of deposition. Under such conditions the internal strength of fine-grained sediments will be reduced. If the reduction is sufficient to lower the shear strength of the deposits below that necessary to balance the shearing force which is induced in the deposits by their position on a slope, failure will take place and a slump will result. Therefore, under suitable conditions of sedimentation, slumping could take place on slopes of very low angles. Once slumping has been initiated it is possible but not necessary that slurrying, as according to Jones's theory, will take place.

As a slumped mass slides down a slope, it will come to rest on other stable or unstable deposits. The load of the slumped mass may induce in these deposits such unstable conditions that they in turn become involved in the slumping, and there is no doubt that many of the huge slumped masses which are known to exist owe their size to their progressive growth in this manner from a comparatively small initial slump.

VI. Sedimentary Volcanism

An examination of the conditions under which sedimentary volcanism occurs suggests that such volcanism is in some way bound up with the compaction of soft sediments. Sedimentary volcanism is a rather uncommon phenomenon, but is sufficiently well known to justify some attempt to explain the controlling conditions for its initiation. Mud volcanoes at present active are definitely confined to areas in which there has been rapid sedimentation during comparatively recent geological times, e.g. late Tertiary to Recent. Fossil mud volcanoes are known, and are found to have been associated with similar conditions of rapid sedimentation. Active mud volcanoes seem also to accompany sediments in which large-scale slumping has taken place. Where mud volcanoes are common, they are found to occur more particularly in places where there has been some tectonic movement in comparatively recent geological times, though such movement may have been slight and, according to some authors, mud volcanoes are often arranged along fault lines. The nature of the outflow itself may vary considerably, and it may be useful to note the different types which can occur.

Kugler (1933) has given a good description of the various types of eruption which have been observed in Trinidad during recent times. Among violently eruptive types of volcano, he gives an instance of one which is estimated to have ejected 500,000 cubic yards of semi-solid mud and rocks in less than twenty minutes. As an example of a more steady type of flow he mentions the Lagoon Bouff volcano. This volcano he describes as an elliptical pool of liquid silty mud, measuring 500 feet by 400 feet, in which salt water and gas are continually discharged. There is a gradation from the Lagoon Bouff type of volcano to others, in which the sediment is only a small proportion of the bulk of the outflowing fluid. The latter type does not protrude above the general level of the surrounding area, since the mud is not solid enough to support itself as a cone. Finally, he infers some relationship between mud volcanoes and salt water springs, which are often of common occurrence in mud volcano areas, and he mentions one such spring which has had a continual flow within living memory of about 500 barrels per day, without any outflow of sediment or gas. Kugler has also noted the occurrence, within the general area in which mud volcanoes are common, of mud flow dykes and sills, these being similar in form to igneous dykes and sills.

Lehner, in the published discussion of the same paper, notes that the ejection of free salt water and liquid mud is restricted to volcanoes which are erupting slowly and continuously. He states that all the material thrown out during the spectacular big eruptions in Trinidad, in the ten years previous to 1933, consisted of large lumps of frothy clay, over which one could safely walk after the eruption had died down.

Oswald (1928) gives similar descriptions of a number of associated vents in the Western Caucasus.

Various theories of the mechanism of mud volcanoes have been suggested, but none which the writer has read has been comprehensive enough to cover all types of eruption, from salt water flow to explosive eruption. Great stress is usually laid on faulting and excessive pressures and the disruptive action of escaping fluids, but few suggestions are made to explain the extreme liquidity of sediments which are often ejected or to give more satisfactory reasons for prolonged salt water flow.

What seems to the writer to be the outstanding fact is that mud volcanoes, and salt water flows which are assumed to be genetically associated with them, occur at present only in areas where there has been rapid sedimentation in recent times, and usually where there has been definite, if slight, tectonic movement. It is to be expected that in areas of rapid, recent sedimentation, the majority of the sediments will be at or near their compaction equilibrium pressures, so that further sedimentation or even slight tectonic movement will result in disturbance of the pressure balance within the sediments, the creation

of hydrodynamic pressures, and the structural weakening of the sediments concerned. Thus, there is no difficulty in visualizing that in mud volcano areas there may be unbalanced sediments with subnormal strength and possible sources of high pressure salt water. Under such conditions there will be a tendency for fluid migration to take place, and if any sediments in which excess fluid pressures have been induced gain access to the surface through tectonically created weakness or other geological causes, the result will be some kind of outflow. The nature of this outflow will depend upon local conditions. In many cases the result will be a spring of salt water only, but a salt water flow may derive sediment either from its source beds or during passage through its vent. The migration of the salt water in the source beds will be similar to migration in a normally compacting series, and therefore migration of oil or gas from the source beds into the vent of the flow may also take place. This explains the mixed flows of many volcanoes. Once a flow has started, its initial causes may be such as to maintain the flow for an indefinite length of time.

The above conception of the causes of steady flow may readily be extended to cases of explosive violence. In this particular instance, the only difference is that access between the unstable deposits and the surface must be gained suddenly, and there must be a large supply of gas available close to the vent at the time of eruption. In such cases, the period of eruption will be too short for the gathering into the vent of a large flow of salt water, and the violence of the eruption may cause great admixture of the primary effluent material with the sediments through which the flow passes. It is therefore to be expected that the expelled material will be of a much more solid consistency than is the case with steady flows.

VII. Conclusion

The object of this paper has been to point out the importance of the rôle which adsorbed water plays during the compaction of sediments, and the impression may have been given that the writer considers that adsorbed water films have a dominating influence during the compaction of finer-grained sediments. This may eventually prove to be the case during the early stages of compaction, but the present state of our knowledge does not permit of any such sweeping statements. There is at present no sound basis of fact by which we can confirm many of the hypothetical details of this paper, and there are many gaps in our knowledge which can be filled only by the vaguest conjecture. It is, however, hoped that this paper will be of interest in indicating some of the more important gaps and in giving some indication of how these gaps may be filled. It is felt that the paper will have a more particular interest for petroleum geologists, in that it has a particular bearing on

the migration of petroleum, and may perhaps ultimately prove to have some bearing on its origin.

Finally, the writer would like to thank his colleagues, Mr. F. R. S. Henson and Mr. J. McGinty, for invaluable constructive criticism while the paper was being written.

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An Experimental Synthesis of Quartz, Albite, and Analcite

By GILBERT WILSON

(PLATE IV)

ABSTRACT

Quartz sand, sodium aluminate and water were heated together in a bomb to above the critical temperature. The apparatus was designed to give a temperature difference of about 100° C. between the two ends of the bomb. Quartz, albite, and analcite were formed in the low temperature end of the bomb.

ABOUT ten years ago, when Dr. Malcolm MacGregor and I were developing our ideas on the granitization problem,[1] we considered that some sort of experimental work might be of value in confirming our theories. Our main thesis was that hot fluids of plutonic origin reacted with the solid minerals of the country rocks and converted them into other minerals which would be in equilibrium with the permeating fluids. The hypothesis of diffusion and reaction in the solid state [2] was not then appreciated by us. The experiments we had in mind were to develop reactions between solid and liquid or soluble chemical components of felspar—albite to begin with—in the presence of water or water vapour at temperatures above and below 375° C., the critical temperature of water.

A bomb having an internal diameter of one inch (2·5 cm.) and length 9 inches (22·5 cm.) was therefore made of special heat-resisting steel. The purpose of having a bomb of such length was to obtain a temperature gradient within it by winding the heating element around one end. In order to minimize internal convection currents the heated end of the bomb was kept uppermost whilst working. Preliminary tests showed us that a range of about 100° could be obtained over the length of the bomb at temperatures of about 400° to 500° C., a range which we expected would suit our purpose.

Two trial runs were made in the first half of 1939, and a third was begun, but had to be discontinued. On the declaration of war University College, London, where the work was being done, was evacuated to Wales; and then in 1940–1 it was seriously damaged during the "Blitz". In consequence our notes were lost except for one loose

[1] MacGregor, M., and Wilson, G., 1939. On granitization and associated processes. *Geol. Mag.*, lxxvi, 193.

[2] Perrin, R., and Roubault, M., 1937. Les réactions à l'état solide et la géologie. *Bull. Serv. Carte géol. Algérie.* Sér. 5, *Pétrographie* No. 1.

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page, but the bomb, some of the products, and a letter from Dr. F. A. Bannister confirming our identifications of minerals formed have subsequently turned up. Details of the length of run and the bomb filling have therefore to be given from memory.

Our second run was the only one from which positive results were obtained. This was an investigation of the reaction between quartz sand and sodium aluminate in the presence of water above the Critical Temperature.

Fine quartz sand was wrapped in a sausage-like bag of silver gauze and bound up with silver wire. The bag had a diameter of about $\frac{5}{8}$ in. ($1\frac{1}{2}$ cm.), and its length was a little less than that of the inside of the bomb. To keep it in place it rested on a support of twisted copper wire at the low temperature end of the bomb. Sodium aluminate, sufficient to convert all the quartz to albite, was dropped into the bomb after the bag of quartz had been inserted, and about one-third of the remaining space was filled with distilled water. The temperature was then slowly raised over a period of two or three days till the hot end of the bomb was at about 500° C. and the low temperature end would be at about 400° C. After a run of approximately two months' duration the bomb was cooled down overnight and opened. Water was still present in the bomb, and the quartz grains in the silver gauze bag had become cemented together by an indeterminate glass-like material, probably hardened gelatinous or opaline silica. Some of the grains were cracked, but the majority seemed unaffected by the treatment.

Development of new crystal growth was, however, found outside the gauze bag on the copper wire that supported it. This, at the low temperature end of the bomb was encrusted with small crystals. Others were also found, but to a lesser extent, on the silver binding wire at the low temperature end of the bag. An original note made at the time states :—

> " At the low temperature end of the bomb (*circa* 400° C.) the supporting copper wire was found to be covered with a crystalline encrustation. The crystals were subdivided into two groups :—
>
> " (*a*) Massive (?), cubic, with good faces, believed to be *Analcite*. Very low birefringence, striated appearance beneath microscope.
>
> " (*b*) Prismatic, radial growths [i.e. little rosettes]. R.I. about 1·53 definitely below Canada Balsam. (?) Twinned, extinguishing at about 15°–16°. Birefringence fairly low. $+^{ve}$, 2V about 75°, axial plane inclined to elongation. At least one good cleavage. (?) *Albite*."

Confirmation of our optical determinations was given to us by Dr. F. A. Bannister of the Department of Mineralogy, British Museum (Natural History) in a letter dated 15th June, 1939 :—

"... X-ray photographs of single crystals are confirmatory. The albite needles are elongated along the c (001) axis. The analcime crystal that I picked off for mounting shows the form (211) and the axis of rotation employed for the photograph was (113) yielding a translation in that direction of 45·4 Å. This divided by $2 \times \sqrt{11}$ gives 13·7 Å which is the unit cell dimension for analcime. ..."

Crystal growths on the silver wire binding the bag consisted of small quartzes. Some of these were still preserved in the material recovered and have been photographed by Dr. G. van Praagh at Christ's Hospital, Horsham. Plate IV.

It is of importance to note that the crystals were formed at and near the lower temperature end of the bomb, which was also the end upon which the bomb stood. Crystal growth was probably determined by the fact that there was a temperature gradient within the bomb. In this case transport of material to the zone of lower temperature must have occurred through the vapour phase. It is, however, possible that there may have been some liquid still existing at the bottom of the bomb, and the presence of such a liquid phase may have been a controlling factor. If our temperature control ($\pm 5°$ as we believed it to be) was accurate, and the lower end of the bomb was at 400° C., there can have been no liquid present until cooling was started, and the rate of cooling relative to the length of experiment was rapid. The precipitation of the crystals from the residual liquid could hardly have taken place during such a short period—overnight—or possibly a bit longer depending on our delay in opening the bomb. This was certainly not more than a couple of days.

If, however, the temperature was not correctly measured, and the lower end of the bomb was below the critical temperature, there must have been some water in the bomb during the whole run. It is possible therefore that the crystal growth occurred only in that part of the bomb where conditions of fairly high temperature and the presence of a liquid phase were realized.

From a point of view of proving granitization processes our initial experiments did not come up to our expectations, but the fact that we were able to synthesize three common rock-forming minerals—quartz, albite, and analcite—under conditions not dissimilar to their occurrence in steam holes in lavas may be of interest.

Our work was greatly assisted by the late Professor H. E. Watson, then Head of the Department of Chemical Engineering at University College, London, who granted us laboratory space and equipment, and gave us valuable technical advice. I would also like to express our thanks to Professor W. B. R. King, who was Head of the Department of Geology, for the encouragement he gave us at the time. Dr. G.

van Praagh has discussed our results with me, and has kindly photographed the quartz crystals we obtained. It was largely at his instigation that this note has been written.

EXPLANATION OF PLATE

Quartz crystals from the silver binding wire near the low temperature end of the bomb. In at least one case pyramidal terminations can be clearly seen (× 50). Photo by G. Van Praagh.

SYNTHETIC QUARTZ CRYSTALS.

Evidence of Fissure Eruption in the Tertiary Lava Plateau of North-East Ireland

By E. M. PATTERSON

ABSTRACT

An example is described of a dyke feeding a lava flow in the Tertiary basalt plateau of North-East Ireland. The dyke has an erratic course and branches into several veinlets, but otherwise it displays the usual characters of a dyke. Continuity between dyke and flow is seen in five places in the restricted area of outcrop of the flow. The possible relationship of the dykes and volcanic plugs of Antrim to the plateau lavas is briefly discussed.

THE problem of the mode of extrusion of the plateau lavas of the North Atlantic Tertiary Province has long been a matter for argument. The original view of Judd (1874) that the lavas were erupted from central volcanoes was followed by Geikie's contrary conception (1897) which held that fissure eruption was responsible for their accumulation, and that the swarms of dykes represent the feeders. More recent reviews of the available evidence have been given by Rastall (1931) and by Richey (1930, pp. 50–55, 1948, p. 39), and crater eruption rather than fissure eruption would appear to be favoured. A contrary view is maintained by Tyrrell (1937, p. 98).

In the British Tertiary area no example has, so far, been recorded of a dyke feeding into a lava flow (Richey, 1939, p. 427). Elsewhere, however, Walker and Davidson give a brief description of two feeders to lava flows in the Faeroes, though it was not possible to decide whether they were dykes or plugs (1936, p. 874). Fissure eruption is favoured by Noe-Nygaard for the Svartenhuk basalts of West Greenland (1942, pp. 66–70). In the latter area, although the evidence is strong, it is indirect and in no case has continuity been proved between a flow and its parent dyke.

Recent field work in the Tertiary lava plateau of North-East Ireland has brought to light what appears to be a dyke feeder to a lava flow. While the occurrence is not claimed to provide unequivocal evidence for the mode of extrusion of the lavas as a whole, it at least forms a small piece of direct evidence which has hitherto been lacking in Britain.

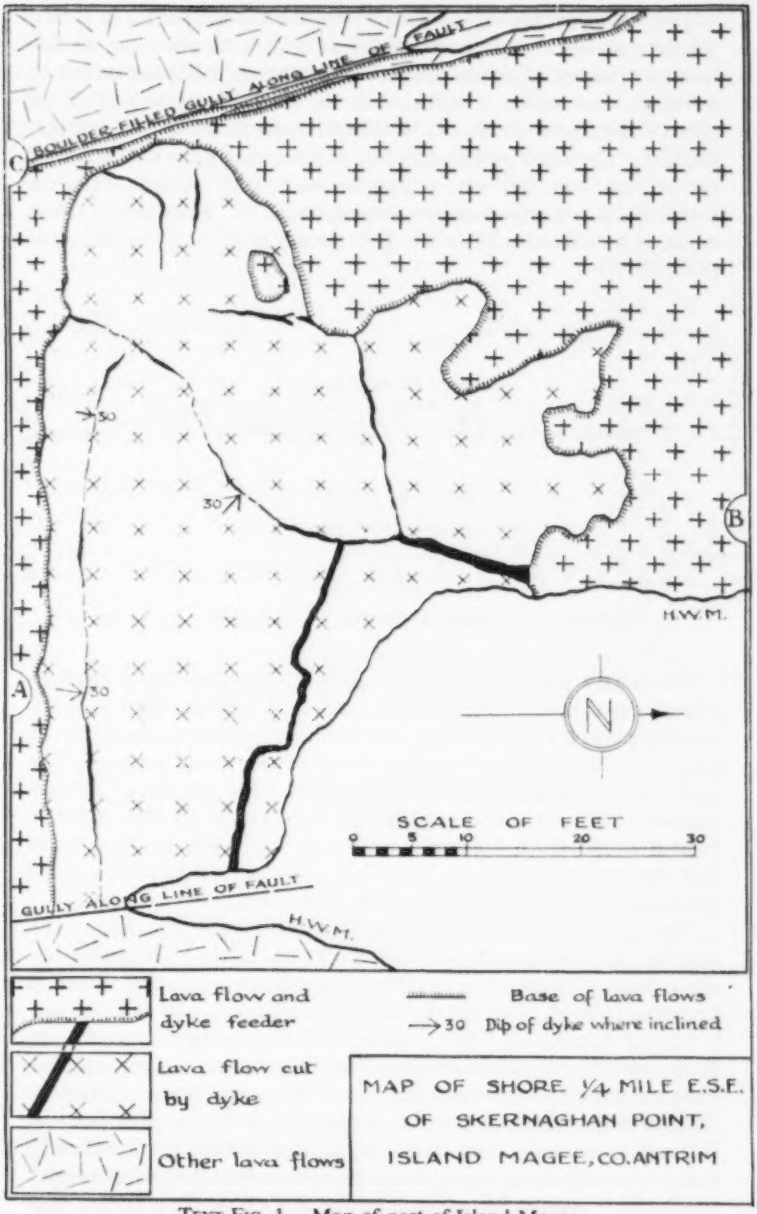
The occurrence is located near Skernaghan Point, the northern extremity of Island Magee, County Antrim. The north coast of Island Magee, from Brown's Bay to Portmuck consists of low cliffs up to 50 feet high, backing the rocky platform of the " 25 foot " raised beach Rock exposures are continuous and consist of a series of flows of basalt, each of which has a thin lateritized top and which belong to the

Lower Basalt Series (Charlesworth, 1935, p. 465). A general description of the geology of the area is given in the relevant Survey Memoir (Hull, 1876). The flows of basalt have a general north-north-easterly dip of around 15°.

On the eastern shore of Brown's Bay the base of the lava series is seen resting on Upper Chalk. The lower flows are all comparatively thin in this part of Island Magee, and the average of 10 feet for the thickness given by Tomkeieff (1934, p. 501) in the Gobbins Cliffs, 5 miles to the south-east, is here more nearly a maximum figure. Many of the flows are only 2 or 3 feet thick, and frequently a thin flow can be seen to taper out altogether when traced laterally. It is not possible to determine precisely the height of the dyke-fed flow above the base of the lava series, in spite of the steady regional dip, since several strike faults of indeterminate throw intervene. The course of these faults is marked by gullies, and they undoubtedly determine the linear trend of the north-eastern coastline of Island Magee. On the published Geological Survey map of the area the lavas are all shown as members of the Lower Basalt Series, and there is no reason to doubt that this is so, since the thick Interbasaltic Horizon outcropping on the west side of Brown's Bay (Cole, *et al.*, 1912) is not seen here, and the lavas of the Upper Basalt Series are generally never so thin as those in this part of Island Magee.

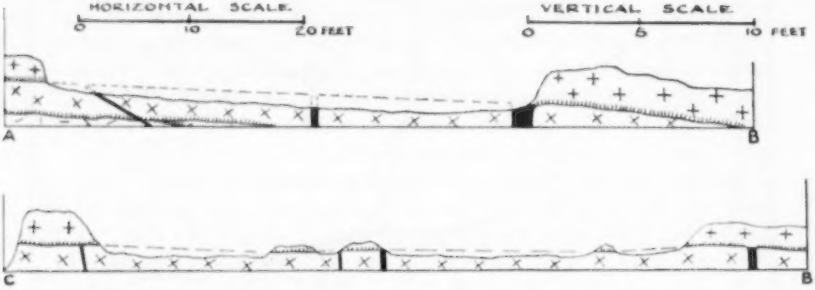
A quarter of a mile east by south of Skernaghan Point a shallow depression in the rock platform exposes as an inlier the upper part of a flow of basalt, which is overlain and partly surrounded by the succeeding flow, the margins of the latter forming a small scarp feature (Text-fig. 1). The inlier measures about 60 by 40 feet, and in it the flow is seen to be intruded by a sinuous and ramifying dyke. Continuity of the dyke and the overlying flow is seen in no less than five places, due to the complex course of the dyke and of the junction between the two flows. No dyke is shown ¼ mile E. by S. of Skernaghan Point on either the published 1 in. Survey Map (Sheet 21) or the original manuscript 6 in. Sheet.

The dyke consists of a main portion and a number of subsidiary veinlets. The main portion is first seen at sea-level on the east side of the inlier, where it has a width of 12 inches. It then follows a course which is sinuous, though in general west-north-westerly, while its width varies between 10 and 12 inches. Thirty feet from the sea it comes to a T-junction, where it turns abruptly and runs north-north-east. The other limb of the " T " is a veinlet, up to 3 inches wide, which locally thins out completely. The portion of the dyke proper, which runs north-north-east from the " T ", can be followed for 16 feet to its junction with the overlying lava flow. Its width, close to the " T ", diminishes to 6 inches, but thereafter it increases to around 15 inches,



TEXT-FIG. 1.—Map of part of Island Magee.

while close to the lava flow which it joins the width is just over 2 feet. Veinlets occur in other parts of the inlier ; some are mere discontinuous stringers of basalt, appearing at intervals along the course of a fissure. The section is restricted in the vertical sense to a height of about 4 feet, but so far as can be seen the dyke rises vertically through the lava. There is a similar difficulty in determining the inclination of the veinlets, but they also appear to be roughly vertical, with the exception of two shown on the map (Text-fig. 1). These dip at a low angle, approximately 30°, towards the main portion of the intrusion (Text-fig. 2).



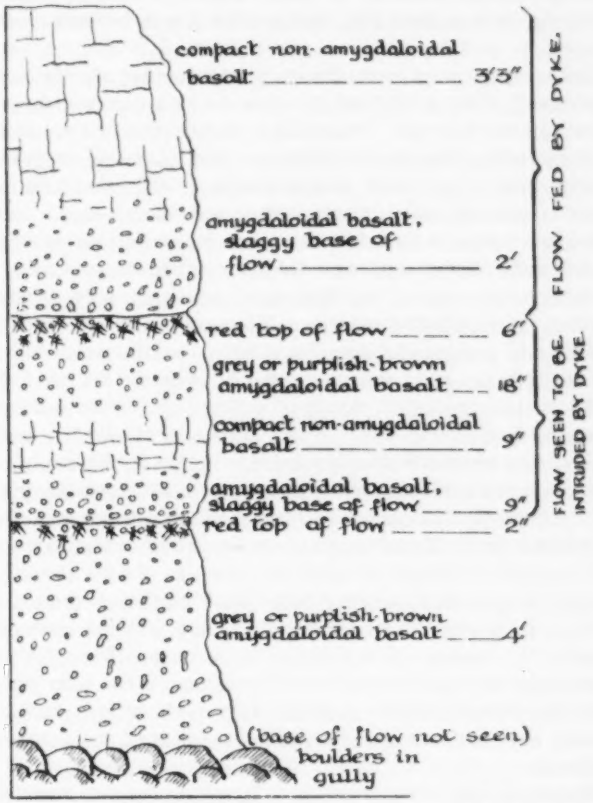
TEXT-FIG. 2.—Horizontal Sections A—B and B—C, Fig. 1.

The central part of the dyke is compact and consists of sparsely amygdaloidal basalt. Towards the margins it becomes finer in grain but amygdales are still present. The weathered surface is pale brown in colour, becoming deeper brown or reddish towards the margins. The surface of the dyke is comparatively smooth, a feature which contrasts markedly with the carious-weathering vesicular basalt lava which it penetrates and which weathers grey or purplish-brown. Jointing is not well developed in the dyke, but where it occurs the joints are more abundant than and unrelated to those of the lava.

The most favourable place for observing the continuity of the dyke and the overlying flow is at the north-east side of the inlier, where the main portion of the dyke reaches its maximum thickness. Here it broadens from 15 to 26 inches over a horizontal distance of 5 feet and a vertical distance of 3 feet. Along with this increase in width, the proportion of amygdaloidal material increases until it is comparable in amount with the slaggy basal portion of the overlying flow. The flow through which the dyke cuts has, in common with the other flows in the neighbourhood, a red lateritized top, approximately 6 inches in thickness, which merges downwards into the normal grey amygdaloidal basalt which overlies the compact centre of the flow (Text-fig. 3). The

dyke is clearly seen to traverse this red top, and thereafter it merges without discontinuity into the slaggy base of the overlying flow. Similar relationships are exhibited by the dyke at the four other points where it joins the lava flow.

Two fault gullies, with courses N. 15° W., lie 70 feet apart on each


compact non-amygdaloidal basalt 3'3"
amygdaloidal basalt, slaggy base of flow 2'
red top of flow 6"
grey or purplish-brown amygdaloidal basalt 18"
compact non-amygdaloidal basalt 9"
amygdaloidal basalt, slaggy base of flow 9"
red top of flow 2"
grey or purplish-brown amygdaloidal basalt 4'
(base of flow not seen) boulders in gully
FLOW FED BY DYKE.
FLOW SEEN TO BE INTRUDED BY DYKE.

TEXT-FIG. 3.—Vertical section through lavas as exposed on east face of fault gully.

side of the inlier (Text-fig. 1). The gully to the east cuts across the course of the dyke and no extension of the latter is seen in that direction. The western gully provides an incomplete section through three flows of lava (Text-fig. 3). Neither the dyke nor its vein offshoots are seen in this gully section, or in the lava flows beyond it. To the north the lavas dip gently below the sea. It is not possible to determine the lateral extent of the

flow fed by the dyke on account of its restricted outcrop. The full thickness is not seen on the rock platform, and the upper part of the flow is obscured by scree and vegetation at the base of the low cliff. It is, however, not more than 10 feet in thickness, and is thus comparable in this measurement with the neighbouring flows. It may be noted that the example illustrated by Walker and Davidson from the Faeroes (1936, fig. 4) is considerably thicker than the flows both above and below it.

The lavas of the Lower Basalts in Antrim are all olivine-basalts (Tomkeieff, 1934, p. 501) which often become coarse enough to be named olivine-dolerites. Microscopic examination of thin sections of the dyke and the lava which it feeds shows that they are petrographically similar, both being fresh olivine-dolerites with subophitic texture. Areas of greenish-brown glass, with curved fracture and a refractive index below that of Canada balsam, are in intersertal relationship to the feldspars. The mineral is provisionally named chlorophaeite. In the lower vesicular part of the flow it is associated with considerable amounts of vermicular chlorite. The amygdales are infilled with chlorite and a colourless granulocrystalline zeolite, which has a very low birefringence and a refractive index of between 1·47 and 1·48, and which may be chabazite. Along its exposed length the dyke margins have a marked reddish-brown colour and are obviously less fresh than the lava into which the dyke is intruded. A thin section cut across the contact confirms this and shows also that the two rocks have a sharp and firmly welded junction. The dyke rock shows marginal chilling; the feldspars have skeletal terminations and are embedded in an opaque matrix consisting largely of secondary limonite. At the actual contact the dyke rock is opaque, apart from small patches of zeolite, and is almost entirely replaced by limonite. The lava adjacent to the dyke is considerably altered. The feldspar laths are pseudomorphed by an almost colourless chlorite, although their outline has been preserved, while the ferromagnesian minerals have been entirely replaced by limonite and serpentine. The zeolitic infilling of the amygdales is unaffected.

There is no doubt that the dyke is later than the lava flow which it traverses. It is also later than the period of lateritic weathering which affected the top surface of the same flow. Its continuity with the overlying, and therefore later, flow is apparent from field examination. The dyke has all the appearance of being intrusive into the flow which it traverses. An alternative hypothesis could be that the dyke was fed from above by the upper flow and had been produced by the infilling of fissures developed in the underlying flow. The fissures must have post-dated the lateritization, otherwise reddening from that cause would have extended down the sides of the cracks, or they would have been

filled by the loose products of subaerial weathering. The development of the cracks must therefore have been penecontemporaneous with the production of the flow which infilled them. Such fissures might conceivably have been the result of earthquake action accompanying the renewed volcanic activity. The absence of any known comparable earthquake structures in other parts of the lava plateau, the firmly welded and chilled contact of dyke and lava flow, and the increase in size and proportion of the amygdales in the dyke as the base of the flow is approached, all seem to the writer to combine to render this interpretation invalid. Here, we appear to have an undoubted instance of a dyke feeding into a lava flow.

In venturing to relate the dyke with the linear swarms of dykes which characterize the British Tertiary Province, the writer was aware that its irregular course appeared to distinguish it from the generally accepted idea of the parallel and tolerably straight dykes which comprise a swarm. It bears no relationship to the marked N.N.W.–S.S.E. tectonic lines which form a marked feature of the district. Such irregularity might even indicate its relationship to a near-by volcanic centre or to a hidden intrusion rather than to a regional dyke swarm. On the other hand, that the detail plan of dykes is often highly irregular has been pointed out by Richey (1939, p. 396), and it may well be that a less intricate plan would be apparent were the course of the dyke visible over a longer distance and the minor features of its course thus capable of being ignored. While it may be fortunate that the dyke in its intricacy, provides five instances of "feeding", it is equally unfortunate that such an irregular course is shown in the limited area of the exposure.

As already stated, it is not felt that this occurrence of necessity proves the mode of extrusion of the vast spread of lavas in the North Atlantic Province, or for that matter of those lavas remaining in N.E. Ireland. The Antrim plateau is the largest remnant of the lava fields of the British Tertiary area, and it is not seen to be associated with any central intrusion-complex or volcano. Numerous dykes are seen in the sub-basaltic sediments and in the lavas themselves, but owing to the paucity of good exposures it is not known what their distribution is within the lavas, or more particularly at different horizons in the lavas (*vide* Noe-Nygaard, 1942, p. 69). There are, moreover, in Antrim numerous large olivine-dolerite plugs frequently elongated in plan from N.N.W. to S.S.E. These plugs, of which upwards of twenty are known, can occasionally be seen to have produced considerable contact metamorphic effects on the surrounding rocks, and they must have acted as conduits for magma over considerable periods. On the other hand, the dykes, in general, fail to effect such marked metamorphism. As Tyrrell has suggested (1937 p. 107), fissure eruption

along dykes may have taken place at an early stage in the formation of the plateau, while later eruptive activity was confined to certain favoured points along the choked dyke-fissure. This localized activity would be represented by the volcanic plugs of Antrim. The change from widespread fissure eruption to local effusion from conelets would doubtless be connected with the continuance or otherwise of the crustal tension which initiated the dyke-fissures. It may be that the comparatively thin flows of the Lower Basalts are products of fissure eruption, as suggested by Geikie, while the thicker flows of these and of the Upper Basalts were erupted from scattered conelets now represented by the dolerite infilled necks. Further examination of the field relationships and the petrography of the rocks concerned is necessary before such a theory can be backed by any body of factual evidence.

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On the Age of the Fauna of the Bugti Bone Beds, Baluchistan

By F. E. Eames (Palaeontologist, The Burmah Oil Co., Ltd.)

Abstract

The vertebrate fauna from the Bugti Bone Beds was at first assigned an Upper Nari age by Pilgrim. Later, he assigned them to the Gaj, on the basis of the identification of three species of *Ostrea* by Vredenburg. Regional field work carried out by members of the geological staff of the Burmah Oil Co., Ltd., showed that the beds really belonged to the Upper Nari after all. Re-examination shows that the identifications of the oysters cannot be upheld, and that there is no palaeontological evidence against the beds being of Upper Nari (Basal Miocene) age. It is therefore necessary to regard the vertebrate fauna as being of Upper Nari (Basal Miocene) age. A list of the species is given for purposes of reference.

THE richly fossiliferous, vertebrate-bearing Bugti Bone Beds, which include horizons also referred to as the Chur Lando Beds, have been of considerable interest for over thirty years. The vertebrate fauna has been described in various papers and memoirs published since 1910 by Pilgrim, Forster-Cooper, Matthew, Colbert, and others, and it constitutes the oldest rich Miocene vertebrate fauna in India or Pakistan.

These beds were first regarded as being of Upper Nari age, and some of the species and varieties were named "*naricus*" or "*naricum*" in consequence of this opinion. Later, Vredenburg (in Pilgrim (1912)) recorded from them three species of *Ostrea* (*Ostrea bicolor* Hanley, *Ostrea vestita* Fuchs, and *Ostrea gajensis* Vredenburg—the latter name being at that time a *nomen nudum*), and on their evidence the beds were subsequently regarded as being of Gaj age. Indeed, Pilgrim later actually changed the names of some forms (quite unjustifiably, according to the International Rules of Zoological Nomenclature) from "*naricus*" or "*naricum*" to "*gajensis*" or "*gajense*", on the basis of the new correlation.

Regional field work carried out by members of the geological staff of the Burmah Oil Co., Ltd. (mainly by Messrs. E. T. Vachell and R. Morrison) showed, however, that these beds were really equivalent to the Upper Nari after all. In view of this it was considered advisable to re-examine the oysters, especially since Vredenburg (1928), in his memoir on the post-Eocene mollusca of "North-West India" made no mention of the Bugti Hills occurrences when dealing with the above-mentioned three species of *Ostrea*. Through the courtesy of the Director of the Geological Survey of India the writer, several years ago, had the opportunity of examining the specimens of these oysters from the Bugti Bone Beds, and it was concluded that there was no palaeonto-

logical evidence against the beds being of Upper Nari age. The examination of the oysters yielded the following information :—

(*a*) One form, referred to as *Ostrea aff. elegans* Linné on the original labels, has coarser ribs than the forms figured by Oppenheim (1903). This is probably the form referred to by Vredenburg, in Pilgrim (1912), as *Ostrea bicolor* Hanley, with which it does not seem to be conspecific. The latter species apparently ranges from Pliocene to Recent, and has only been recorded as a fossil from India or Pakistan from the Gwadar Stage (Pliocene) of Gwadar, Mekran Coast, Baluchistan.

(*b*) A second form has less distinct ornament, a different umbonal curvature, and a more triangular outline than *Ostrea* (*Crassostrea*) *gajensis* Vredenburg, which occurs in the Upper Gaj (Burdigalian) of Western Pakistan and Western India and in equivalent beds in Burma. It is much less foliaceous and more curved umbonally than *Ostrea vestita* Fuchs (1883), which is a Miocene form that has been recorded from the Gaj of Western Pakistan and western India, and from the Basal Manchhar of Western Pakistan.

(*c*) A third form is somewhat similar to forms from Western Pakistan and Burma that Vredenburg (1928) referred to *Ostrea fraasi* Mayer-Eymar (see Oppenheim, 1903), but the lower valve is apparently deeper, the shell not so high, and the attachment area very large. The forms referred by Vredenburg to *Ostrea fraasi* Mayer-Eymar do not seem to belong to that species, since the lower valve is not gibbous and has a large attachment area ; Mayer-Eymar's species is, moreover, of Eocene age.

(*d*) A fourth form is *Ostrea* (*Lopha*) *hyotis* Linné, a well-known form ranging from Aquitanian to Recent, and with which the writer believes *Ostrea protoimbricata* Vredenburg (1928) from the Lower Nari (Oligocene) to be conspecific.

In another paper the writer has recorded that the widespread and important unconformity associated with the Miocene/Oligocene boundary in Burma and Assam has been recognized (by Mr. W. B. Metre, of the Burmah Oil Co., Ltd.) in Western Pakistan and Western India at the Upper Nari/Lower Nari boundary. The horizon is marked, as in Burma, by unconformity and a palaeontological break, and as in Assam by unconformity.[1] While the Lower Nari is of Oligocene age, the Upper Nari is of basal Miocene age, and would be more appropriately grouped with the Gaj Series, the upper part of which Vredenburg has shown to be of Burdigalian age.

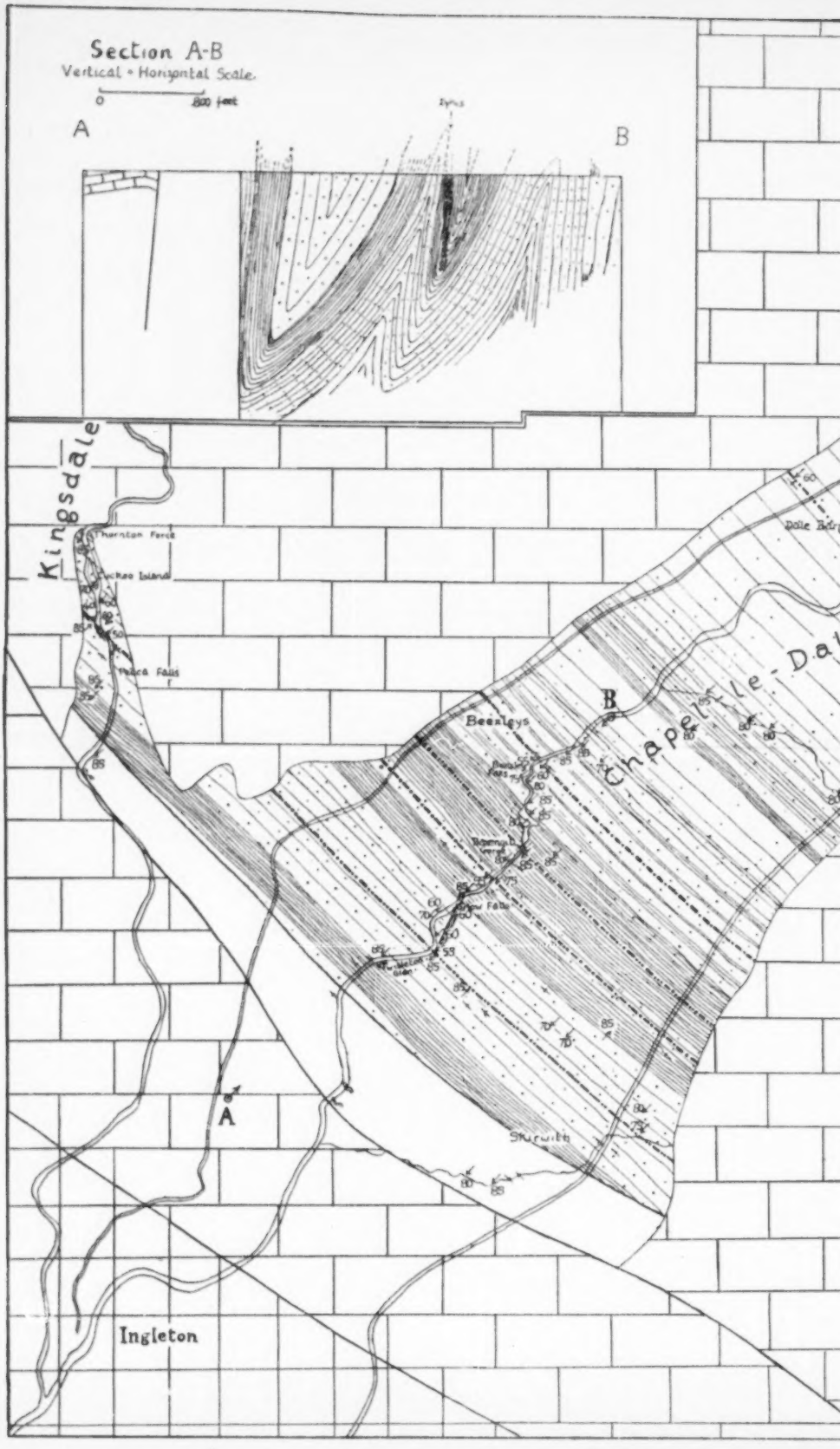
[1] Owing to the poorly fossiliferous nature of the Assam rocks a palaeontological break is not evident ; it is possible that further work on the microforaminiferal faunas may discover one.

Both marine Lower Nari beds containing large foraminifera (*Nummulites*, etc.) and the vertebrate-bearing Upper Nari beds occur in the Bugti area. Whether or no there is more than one fossiliferous horizon in the Upper Nari is not known, but the fauna as a whole is of basal Miocene age. The writer understands from Dr. A. T. Hopwood that there is no element in the fauna against such a view; indeed, Dr. Hopwood considers that *Trilophodon cooperi* Osborn is at an earlier stage of development than species of this genus found in the Burdigalian of France.

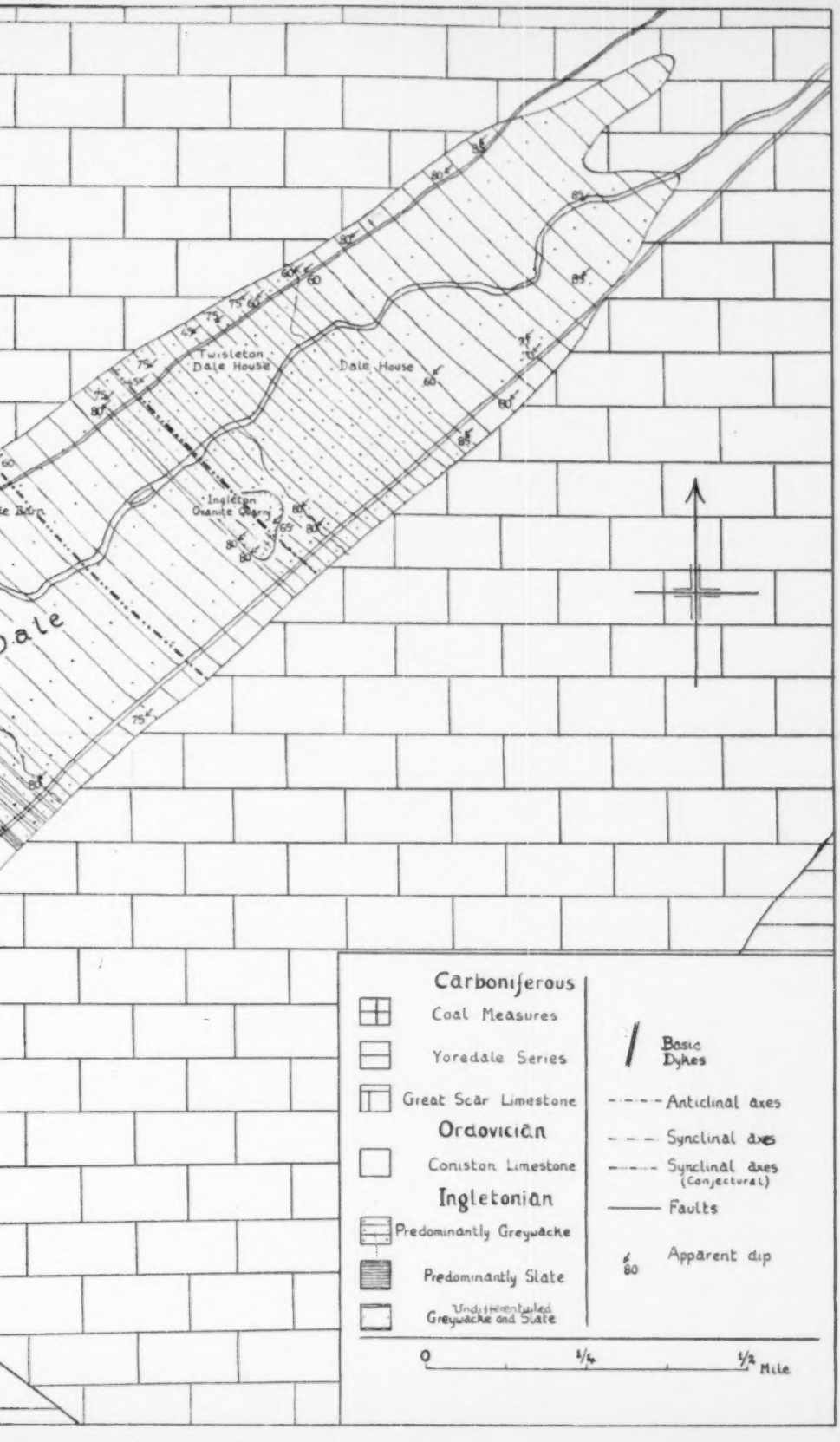
No complete faunal list of the vertebrates from the Bugti Bone Beds (including the Chur Lando Beds) appears to have been published, and it is hoped that the following list, many of the records being type occurrences, will be useful :—

Mammalia

Aceratherium abeli Forster-Cooper
Aceratherium bugtiense Pilgrim
Aceratherium gajense (Lydekker)
Aceratherium perimense (Falconer & Cautley)
Amphicyon cooperi Pilgrim
Amphicyon shahbazi (Pilgrim)
Ancodus ramsayi Pilgrim
Anthracotherium adiposum Forster-Cooper
Anthracotherium bugtiense Pilgrim
Anthracotherium exiguum Forster-Cooper
Anthracotherium ingens Forster-Cooper
" *Anthracotherium* " *punjabiense* Lydekker
Anthracotherium sminthos (Forster-Cooper)
Baluchitherium osborni (Forster-Cooper)
Brachyodus africanus Andrews
Brachyodus borbonicoides Forster-Cooper
Brachyodus gandoiensis Forster-Cooper
Brachyodus giganteus (Lydekker)
Brachyodus hyopotamoides (Lydekker)
Brachyodus indicus Forster-Cooper
Brachyodus orientalis Forster-Cooper
Brachyodus pilgrimi Forster-Cooper
Brachyodus platydens Forster-Cooper
Brachyodus strategus Forster-Cooper
Bugtitherium grandincisivum Pilgrim
Cadurcotherium indicum Pilgrim
Chilotherium blanfordi (Lydekker)
Chilotherium intermedium (Lydekker)
Chilotherium smith-woodwardi (Forster-Cooper)
Deinotherium indicum (Falconer) var. *gajense* (Pilgrim)
Diceratherium minus (Lydekker)
Diceratherium shahbazi Pilgrim
Gelasmodon gracilis Forster-Cooper
Gelocus (?) *gajensis* Pilgrim
Gelocus indicus Forster-Cooper
Gonotelma major Forster-Cooper
Gonotelma shahbazi Pilgrim
Hemimastodon crepusculi (Pilgrim)
Hemimeryx affinis Pilgrim (*nomen nudum*)
Hemimeryx lydekkeri Forster-Cooper



GEOLOGICAL MAP OF THE INGL



THE INGLETON INLIER, YORKSHIRE.

Hemimeryx speciosus Pilgrim
Hyaenaelurus bugtiensis (Pilgrim)
Hyoboops (*Merycops*) *longidentatus* (Pilgrim)
Hyoboops minor Forster-Cooper
Hyoboops naricus Pilgrim
Hyoboops palaeindicus (Lydekker)
Listriodon affinis (Pilgrim)
Metamynodon bugtiense Forster-Cooper
Metarctos (?) *bugtiensis* (Forster-Cooper)
Parabrachyodus obtusus (Forster-Cooper)
Paraceratherium bugtiense Forster-Cooper
Paraceratherium (?) *churlandense* Forster-Cooper
Phyllotillon naricus Pilgrim
Prodremotherium (?) *beatrix* Pilgrim
" *Propalaeomeryx* " *exiguus* (Pilgrim)
Schizotherium pilgrimi Forster-Cooper
Telmatodon bugtiense Pilgrim
Telmatodon orientale Forster-Cooper
Trilophodon cooperi Osborn
Xenochoerus (?) *jeffreysi* (Forster-Cooper)

Reptilia

Crocodilus bugtiensis Pilgrim
Gavialis breviceps (Pilgrim)
Gavialis curvirostris Pilgrim

The above list is drawn from all sources known to the writer. Any complete bibliography would occupy a large amount of space, and consequently none is given. All volumes of the *Palaeontologia Indica*, the *Records* and *Memoirs* of the Geological Survey of India, as well as the well-known papers and monographs in other publications by such authors as Hopwood, Forster-Cooper, Matthew, Colbert, Osborn, etc., have been consulted ; from these less well-known references have been extracted. It has been found that a fair number of Pilgrim's earlier records of species must rank as *nomina nuda*, although apparently only one case is involved here. The writer has, as far as possible, followed the International Rules of Zoological Nomenclature.

The writer is indebted to the Directors of the Burmah Oil Co., Ltd., for permission to publish this paper.

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A Restudy of the Ingletonian Series of Yorkshire [1]

By G. P. LEEDAL and G. P. L. WALKER
(Department of Geology, University of Leeds)

(PLATE V)

ABSTRACT

A description of the Ingletonian Series is given, with special reference to the sedimentary structures which occur and their use in determining the nature of the folding of the beds ; this is shown to be isoclinal. The age of the series is discussed, and it is considered to be in all probability Pre-Cambrian.

INTRODUCTION

THE name Ingletonian Series was given by Rastall to a group of unfossiliferous slates and grits occurring in the West Riding of Yorkshire at Ingleton and Horton-in-Ribblesdale. The formation is unconformably overlain by the Carboniferous Limestone, and on the south is faulted against Lower Palaeozoic rocks. In the present work the evidence of current and graded-bedding has been applied to the determination of the structure of the series. As yet, no undisputed fossils have been described, and the age of the series is uncertain ; new evidence bearing upon this is discussed.

The most important exposure of the Ingletonian rocks occurs in the valleys of Chapel-le-dale and Kingsdale, near Ingleton, and most of the present description applies to this area. In the lower parts of the two valleys there are continuously exposed river sections, but above the farmhouse of Beezleys, in Chapel-le-dale, the outcrops are scattered and discontinuous, although a good section is exposed in the Ingleton " Granite " Quarry.

LITHOLOGY

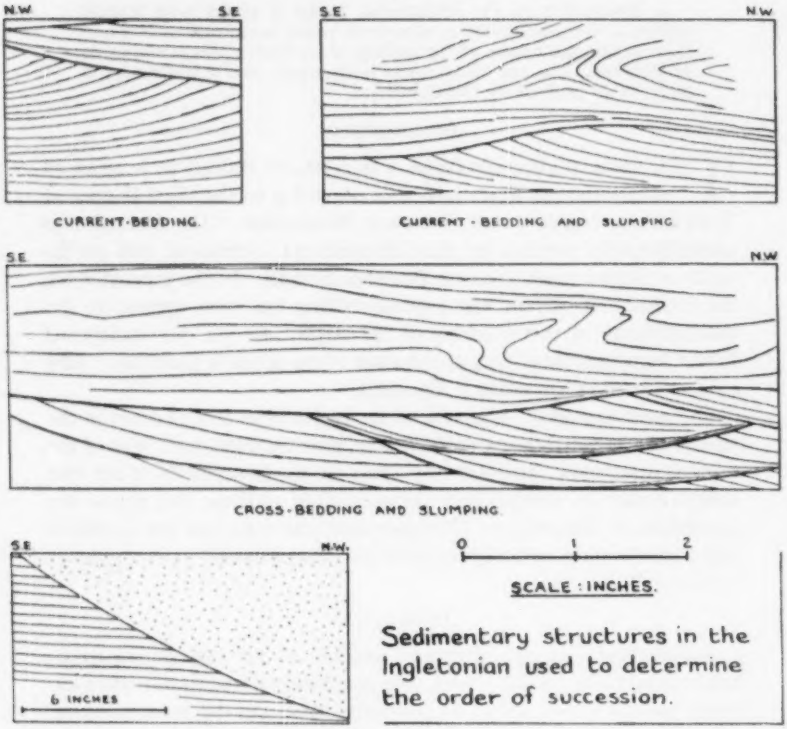
A comprehensive petrographical account of the Ingletonian rocks has been given by Rastall (1906), who has distinguished three main rock types, namely slates, grits, and conglomerates. On the accompanying map of the Ingleton Inlier (Pl. V) we have used the term greywacke, in preference to the indefinite term grit, and have distinguished the following lithological divisions of the series, (i) predominantly greywacke, (ii) predominantly slate, (iii) undifferentiated greywacke and slate. There are all transitions from massive greywacke into finely laminated slate. Banded series of slates and greywackes, with the individual beds only a few inches thick, form transitions between groups (i) and (ii). Coarse greywacke beds occur in many parts of the inlier, rarely more than a few feet thick ; an exception to this is the

[1] Since this paper was written we have learnt that Dr. G. Bond has been working on the Ingletonian and has reached conclusions similar to our own. He has kindly withdrawn his claims in our favour.

coarse greywacke in the Ingleton " Granite " Quarry, which is up to 100 feet in thickness.

Sedimentary Structures

Three sedimentary structures of special importance will be described, namely current-bedding, graded-bedding, and slump-folding.



Text-fig. 1.

Current-bedding.

Current-bedding occurs throughout the Ingletonian strata, but is best developed in the medium-grained greywacke beds. The commonest type may be termed recurrent-diagonal bedding, in which the foreset laminae of each bed are cut off at the base of an overlying, and asymptote against the underlying, stratum. Torrent-bedding is sometimes seen in which the truncation occurs against the upper and lower strata. Cross-bedding simulating aeolian bedding on a small scale is frequently seen. Text-fig. 1 shows typical examples of the above types

of current-bedding ; attention should be drawn to the small scale of the structure.

Graded-bedding.

Graded-bedding has been seen in a few coarse greywacke beds distributed sporadically in the Ingletonian. In the typical case there is a transition from coarse greywacke, up through finer greywacke, to slate. The coarse greywacke bed in the Ingleton " Granite " Quarry has a basal conglomerate containing rounded and angular pebbles of finer-grained greywacke ; this is an example of graded-bedding on a large scale.

Contemporaneous slump-folding.

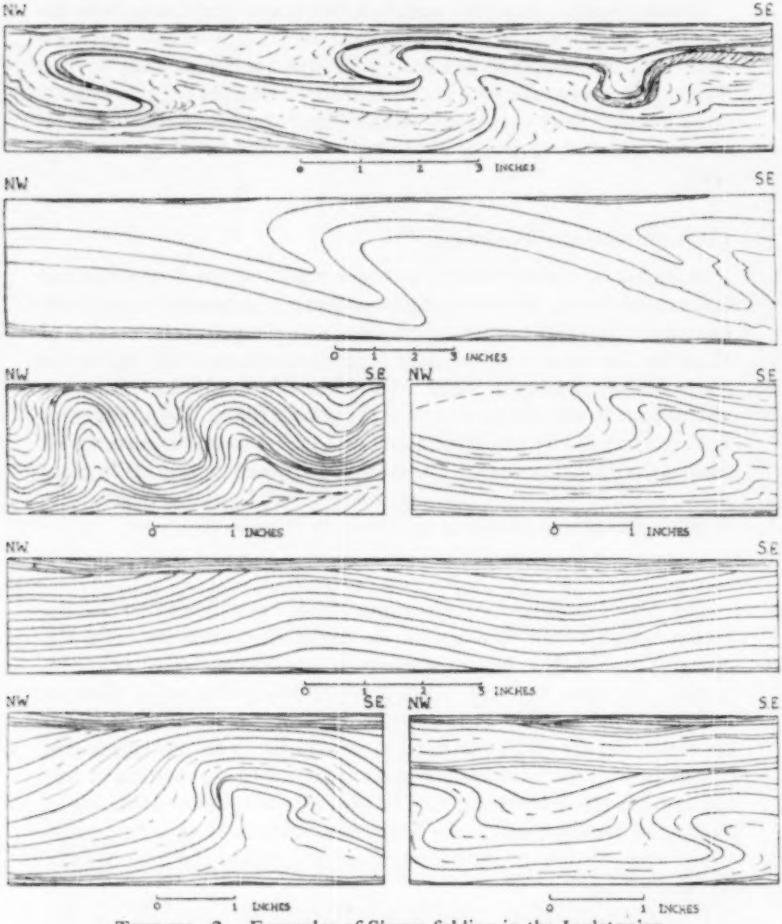
Slumping of unconsolidated sediment has occurred throughout the Ingletonian Series. It is particularly well seen in greywacke beds, rarely more than a few inches thick, interbedded with slate. Good exposures of slumping can be seen in the slate quarry near Snow Falls and in the river sections at Beezley Falls. There are all transitions from mere undulations in the slumped beds to recumbent folds. The slumping is not accompanied by any brecciation, and the folds are often truncated against the overlying strata. The slumping appears to have taken place down a plane of deposition having a general north-westerly dip. Typical examples of slumping are shown in Text-fig. 2.

The above sedimentary structures have been employed in the determination of the structure of the Ingletonian since they give the direction in which a group of strata is " younging " (Bailey, 1934, p. 469). It must be emphasized that the interpretation of current-bedding in the Ingletonian is attended by several difficulties, of which the following are the most important : (i) the beds are extensively fractured, with the fractures commonly inclined to the bedding at low angles ; (ii) torrent-bedding may be confused with current-bedding in the case of imperfect exposures ; (iii) the current-bedding is on a small scale ; and (iv) it is usually necessary to clean rock surfaces to observe current-bedding.

The evidence from the bedding and lithology demonstrates that the Ingletonian was deposited in fairly shallow water subject to current action. As deduced from the current-bedding, the prevalent direction of the currents supplying the sediment was from a general south-easterly direction. The series is lithologically comparable with parts of the lower Torridonian, and may be compared to this group of strata in its mode of deposition.

The Ingletonian of Horton-in-Ribblesdale

Greywackes and slates of the Ingletonian Series are seen in a few exposures near Horton-in-Ribblesdale, where the strike is nearly east–west and the beds are steeply inclined southwards. In the railway



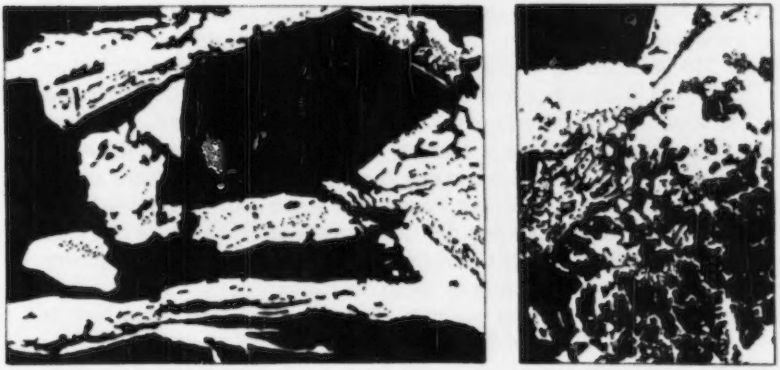
Text-fig. 2.—Examples of Slump-folding in the Ingletonian.

cutting south of Horton station there are two good exposures of greywackes and slates which are particularly interesting on account of the associated calcareous rocks.

At the northern end of the south exposure in the cutting a breccia consisting of angular fragments of greywacke in a matrix of crystalline

limestone occurs. This exposure has been re-examined and clear evidence for replacement of the greywacke by calcite on a large scale has been obtained. It is believed that this breccia is to a large extent a replacement breccia.

At the southern end of the cutting a 3 ft. band of fossiliferous crystalline limestone occurs, more or less conformable to the bedding, and from which King (1932) has obtained an Ashgillian fauna. He has presented convincing evidence that this band represents a neptunean


Diagrams illustrating replacement of Ingletonian grit (black) by calcite (white). Railway cutting S. of Horton-in-Ribblesdale.
0
1
2
SCALE: INCHES.

TEXT-FIG. 3.

dyke. However, part of the band, that part described by King as poorly fossiliferous, is in part due to replacement of greywacke by calcite.

That replacement has occurred in the above cases is clearly seen from the diagrams (Text-fig. 3). One effect of this replacement is seen in the development of angular fragments, previously considered to result from erosion brecciation and desiccation. In addition to the macroscopic evidence of corrosion and replacement, the grits are frequently seen to be permeated by calcite on a microscopic scale.

TECTONICS

Folding.

In Chapel-le-dale the Ingletonian beds show an apparent south-westerly dip at high angles over a distance of 2¼ miles. This has been taken to indicate that at least 10,000 feet of tilted strata are exposed (Gunn, 1890, p. 5), but Hughes (1902, pp. 325–6) expressed doubts

regarding this. He observed folds near Dale Barn and in the " Granite " Quarry, and therefore regarded the series as being isoclinally folded, and drew a hypothetical section to illustrate this view. Other observers either do not appear to have seen these folds or else have doubted their existence. It is now abundantly clear, from a study of the current and graded-bedding that the Ingletonian is isoclinally folded. The strike is almost exactly N.W.–S.E., and is very constant throughout the inlier. The beds are almost always inclined to the south-west at high angles, usually greater than 75°. In the Ribble Valley the Ingletonian strikes 10° N. of W., and the apparent dip is generally about 70° towards the south.

To illustrate the folding, sections in lower Kingsdale and Chapel-le-dale will be described in some detail. In Kingsdale the axis of a syncline is seen a few yards north of the uppermost of the Pecca Falls. The river runs along the axis for a distance of 80 yards. The dip of the north limb is as low as 40°, increasing rapidly upstream to 70° at Cuckoo Island and 85° at Thornton Force. The south limb of the syncline is inverted with an apparent dip downstream of 80°–85° ; at the axis, however, this limb dips upstream at a high angle. The folding is very sharp, and is accompanied by much fracturing.

The syncline appears again in Chapel-le-dale. The actual axis is not well seen, though there is a contrast in the dips on either side of it ; the presence of the axis is shown by a slight topographic depression which runs along it. The dips of the two limbs are similar to those seen in Kingsdale. The presence of the syncline is confirmed by evidence from current and graded-bedding determinations made in both valleys. Further evidence is obtained from the lithology ; upstream and downstream from the axis of the syncline occur two slate bands of closely similar thickness and lithology, which are sharply differentiated from the massive greywacke beds within the syncline. They outcrop at almost equal distances from the axis, and the slight difference which does occur is probably due to the asymmetric nature of the fold, the axial plane of which dips to the south-west at about 70°.

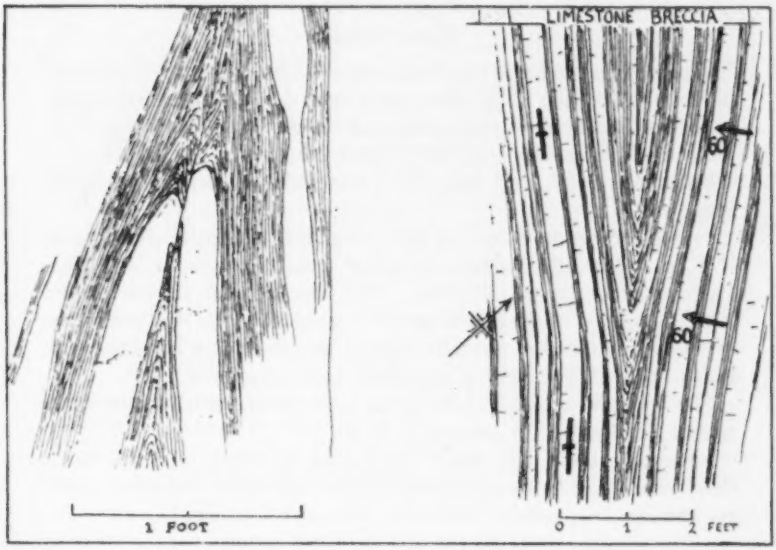
An anticline is seen in the river in Chapel-le-dale about 100 yards south-east of Beezleys and a few yards above the uppermost of the waterfalls. A sketch of the river section, showing the fold, is reproduced in Text-fig. 4. The presence of this anticline was proved by current-bedding determinations at places within 30 yards upstream and downstream from the axis. The dip of the south limb is 60°, whilst the north limb is essentially vertical.

Between this anticline and the previously described syncline two further folds have been proved by current-bedding. They consist of an anticline and a syncline, and the former can be observed in the river 60 yards upstream from the slate quarry near the Snow Falls. The

synclinal axis must fall in the middle of the slate band outcropping up the Baxengill Gorge, and this precludes its recognition in the field.

In view of the nature of the outcrops north of Beezleys, in Chapel-le-dale, it is impossible to map accurately all the folds which must occur. A synclinal axis crosses the valley near Dale Barn (Text-fig. 4) and a syncline occurs in the Ingleton " Granite " Quarry, though the actual axis is not well seen, owing to intense fracturing in the greywacke beds.

Summarizing, we may briefly state that the Ingletonian Series of the Ingleton Inlier is isoclinally folded into a succession of anticlines and



TEXT-FIG. 4.—Left: Sketch of section of anticline above Beezley Falls. Right: Plan of syncline near Dale Barn.

synclines, which have axial planes dipping south-west at about 70° (Pl. V, section). The southern limbs of synclines and the northern limbs of anticlines are therefore inverted. It would appear that the main direction of pressure came from the south-west. A relatively small thickness of strata outcrops over the 2¼ miles of the exposure in Chapel-le-dale.

Fracturing.

The Ingletonian rocks are intensely fractured on both a large and a small scale. The lack of distinctive beds within the series makes it impossible to determine the nature of the fracturing accurately. A large

fault is exposed at the northern end of the Ingleton " Granite " Quarry and a brecciated zone about 5 feet wide occurs. The fault plane is horizontally slickensided and is parallel to the bedding, which dips at 65°. Small faults with a few inches displacement are common. The shear fractures are usually inclined to the strike at small angles. Tension fractures are very common in the greywacke beds and have been infilled with quartz. They trend approximately N.N.E.–N.E., and are inclined to the south-east at high angles. Quartz veins with this trend are rarely more than a few inches thick. Veins trending approximately with the strike are not uncommon, and may occur up to 2 feet in width.

Basic Dykes

A pair of basic dykes cut the Ingletonian in Chapel-le-dale. Exposures of these dykes occur in the slate quarry near the Snow Falls and in the river immediately below the quarry, and also further downstream at the head of Twisleton Glen, on the left bank of the river. The dykes are a few feet apart and are 1 foot and 3 feet wide at Snow Falls. Their trend is N.N.E.

In thin section the dykes are seen to be much altered, and consist of chlorite, calcite, plagioclase, secondary quartz, leucoxene, and ore. Large pseudomorphs of chlorite and calcite after olivine occur. A determination of the quartz content was made by R. W. Grimshaw, by measuring the β to α quartz thermal energy change, and the result showed that 13·2 per cent of secondary quartz is present.

The dykes have been sheared subsequent to their intrusion and are typical members of the greenschist facies.

Regarding their age, these dykes may be related to the early Ordovician basic intrusions of the Cross Fell Inlier (Hudson, 1937, pp. 396–8).

Age Relationships of the Ingletonian

In the lower part of Chapel-le-dale and Kingsdale a narrow outcrop of much crushed Coniston Limestone occurs. The junction with the Ingletonian is regarded as being faulted (Wood, 1948). It is now known that the Ingletonian is inverted immediately north of the Coniston Limestone outcrop, and there can be little doubt that no conformable passage exists between the two formations.

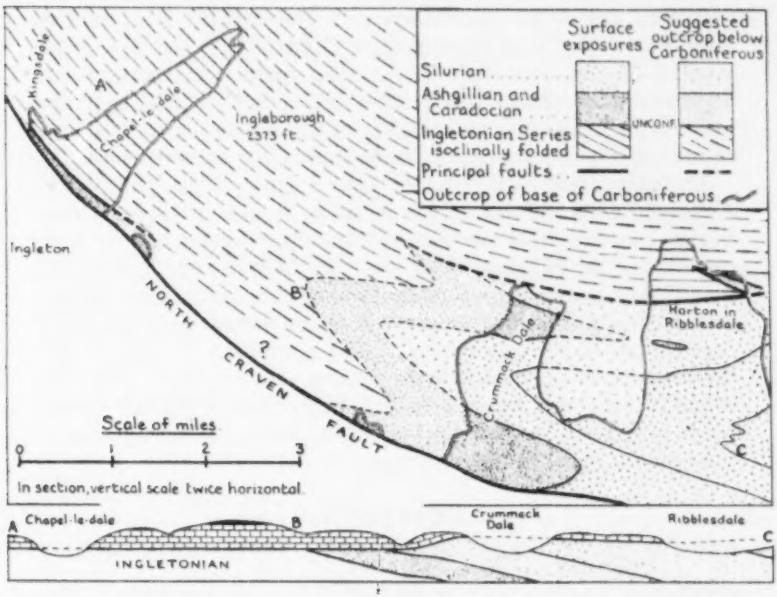
With regard to the age of the Ingletonian, there are three possibilities :—

(1) That the Ingletonian is of Ordovician age and passes up conformably into the Coniston Limestone Series ;

(2) that it is of Lower Palaeozoic age and is overlain unconformably by the Coniston Limestone ; and

(3) that it is Pre-Cambrian.

Green (1917) supported the first view. A correlation of the Ingletonian with the Ordovician strata of the Lake District and Wales was denied by Rastall, on petrographic grounds. Rastall and King considered the Ingletonian to be older than the Ordovician, and possibly of Pre-Cambrian age. Regarding the neptunean dyke at Horton-in-Ribblesdale, King states (1932, pp. 107–8): "after the deposition of the Ingletonian, sufficient time elapsed to allow the grits



TEXT-FIG. 5.—Map and section showing relationship between the Ingletonian Series and the fossiliferous Lower Palaeozoic strata.

to become consolidated, tilted to a steep angle, and eroded . . . prior to Ashgillian times . . ." and as " no period of intense earth movement is known during the Ordovician or Cambrian it would appear . . . that the compressional movements . . . must belong to Pre-Cambrian times ".

The occurrence in the Ingletonian of isoclinal folding stands in marked contrast to the more open folding in the adjacent fossiliferous Lower Palaeozoic rocks of Crummackdale and Ribblesdale (King and Wilcockson, 1934). It is therefore considered that the former has been affected by at least two periods of folding of pre-Caradocian and Caledonian age, the latter also affecting the fossiliferous strata. It may be that all the folding in the pre-Carboniferous rocks was accomplished

at one period, the difference in intensity being due to some structural cause, but the neptunean dyke at Horton, to which reference has already been made, provides clear evidence that slates already existed in the Ingletonian Series in Caradocian times, which would seem to preclude this possibility.

The general relationships of the Ingletonian to the fossiliferous Lower Palaeozoic strata are shown in Text-fig. 5. An unconformity has been drawn below the Caradocian, and the outcrops have been tentatively continued below the Carboniferous. The easterly pitch of the fossiliferous strata at an angle of about 7° should be noted, this would account for the occurrence of the older Ingletonian rocks in the Ingleton area. Attention is also drawn to the general parallelism of the strike of the Ingletonian and the adjacent Lower Palaeozoic strata, and to the way in which the Craven Fault System follows this strike.

An unconformity occurs in the Lake District at the base of the Coniston Limestone, and there is evidence for slight pre-Bala folding. In the Cross Fell Inlier (Shotton, 1935) an unconformity has not been proved, but the Skiddaw Slates are more intensely folded than the post-Skiddavian rocks, and have therefore presumably been folded during an early Ordovician orogeny. In neither of these areas, however, does the pre-Caradocian folding appear comparable to that of the Ingletonian ; this fact, taken in conjunction with the absence of fossils within the series and the impossibility of correlating it with any of the North of England Lower Palaeozoic strata, seems to indicate that it is in all probability of Pre-Cambrian age.

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CORRESPONDENCE

REMARKS ON DR. LAMONT'S INTERPRETATION OF FEATURES IN THE TRILOBITE *PLATYCALYMENE*

SIR,—In a recent number (*Geol. Mag.*, lxxxvi, 1949, 313, 314) Dr. Lamont records that *Platycalymene duplicata* (Murchison) has two pairs of anterior pits lying in the axial furrows each pair respectively in front of and behind the ocular ridges. He claims that these point to a trisegmental origin of the frontal lobe of the glabella, a claim here considered to be based upon a misapprehension.

The anterior pair of pits seen in *P. duplicata* are familiar features among various of the Calymenid genera—these are the "antennary" pits of Shirley's descriptions (*Quart. Journ. Geol. Soc.*, 1936). *Platycalymene* shares with *Metacalymene* and *Pharostoma*, among Calymenid genera, the presence of an ocular ridge or eye-line. Now, it is frequent in trilobites that when a ridging occurs in the exoskeleton there is a tendency for the development proximally of a complementary furrow. As examples may be quoted the cephalic marginal rim and marginal furrow, also the palpebral lobe and palpebral furrow seen in several genera. In a specimen of *Platycalymene duplicata* from Pencerrig, Builth, preserved in the Geological Survey and Museum, numbered 19565, the cranidial shield shows such a complementary furrow behind the ocular ridge and the ridge crosses the axial furrow to merge into the frontal lobe of the glabella, and in so doing it takes with it the complementary furrow which impresses itself into the axial furrow, forming the hindermost of the two anterior pits to which Dr. Lamont draws attention. It is possible that this hindermost pit had some indirect relationship to a corresponding hypostomial structure, but it is very doubtful whether it has any bearing on the primary segmentation of the trilobite head.

The presence of a near ally of *P. duplicata* at Newtown, Co. Waterford, has long been known, e.g. Salter, *Monograph of the British Trilobites*, 1865, p. 101; Stubblefield, *Geol. Mag.*, 1939, p. 59. The Newtown cranidium, collected by Austin nearly 100 years ago, to which these previous writers have referred, is preserved in the Geological Survey and Museum and numbered 56721; it is not compressed laterally in distinction from the appearance of Dr. Lamont's holotype of his species *P. éire*. The pre-ocular course of the facial sutures is much as Dr. Lamont describes, though that author is inaccurate in his description of the course in *P. duplicata* from Builth. As shown by Salter, op. cit., pl. ix, fig. 20, in *P. duplicata*, the pre-ocular courses are parallel for the greater part of their length, as in *P. éire*; furthermore, judging from Austin's specimen, the undistorted anterior border-rims are similar in the two species, as also is the distribution of the glabellar furrows. The tendency for the lateral parts of the occipital ring to point forwards exists not only in Dr. Lamont's material of *P. éire* but also in some *P. duplicata*, e.g. G.S.M. specimen 19557; this may be a preservational feature resulting from differing pressures; the Austin specimen does not show such a tendency. It is, of course, conceivable that Dr. Lamont's specimen of *P. éire* is not conspecific with the fossil collected by Austin from Newtown; but with Dr. Lamont's description in print, without reference to the earlier Austin specimen, it is likely that the latter would be taken in default as *P. éire* by workers unfamiliar with the material, and the remarkably close resemblance between Austin's specimen and the Builth *P. duplicata* would be ignored. The major difference between these two forms appears to me to be that whereas in *P. duplicata* the occipital ring is $\frac{1}{3}$ to $\frac{1}{2}$ of the posterior width of one of the fixed cheeks, in the Irish specimen these are approximately equal in width; should better material come to hand from Dr. Lamont's locality this feature may be checked, and the true characters of *P. éire* may become established.

C. J. STUBBLEFIELD.

GEOLOGICAL SURVEY AND MUSEUM,
LONDON, S.W. 7.
December, 1949.

HILT'S LAW AND THE VOLATILE CONTENTS OF COAL SEAMS

SIR,—From Prof. O. T. Jones's article in the last two numbers of the *Geological Magazine*, on the volatile content of coal seams, in which my name figures so frequently, it may well appear to the majority of your readers that I am a believer in the so-called "law" of Hilt, and that I have devised a formula which supports it. This impression is created by a series of substitutions, of which one may be taken by way of example. The formula $V^2 \propto y$ with V representing the volatiles of the coal seam and y a *depth* below a given datum, is attributed to me, whereas the formula given in my original paper (*Q.J.G.S.*, civ, 404–5) is $V^2 \propto d$, with V representing *twice* the volatile matter and d representing a *distance* measured at right-angles from a particular plane of shear or stress. My South Wales formula has nothing to do with Hilt's "law", but the substitute is one of Prof. Jones's many experimental variants of the "law".

Your readers will be disappointed to find in this article unintelligible numerals and symbols substituted for the real values of the volatiles of coal seams. If a formula warrants testing and the results of the test are thought to be worth publishing, the calculated results should be given side by side with the actual known results. By this means, the reader may assess the value of the formula himself, and if he so pleases, he can amuse himself with differences, sums of differences, the square of the sums of differences, or any other variations of simple arithmetical exercises: but the reader should be given real values, not symbolic substitutes. The value of Prof. Jones's own arithmetical exercises may be assessed from the following quotation, which purports to elucidate one of his symbolic tables. "It may appear strange that given data, representing volatiles and depths, can conform in varying degrees of approximation to such diverse laws [*sic*] as $V \propto y^2$ and $V^2 \propto y$." Since $V \propto y^2$ is the same as $V^2 \propto y^4$ then if we let y equal 2,000 feet (the depth mentioned in Prof. Jones's next sentence) with one "law" $V^2 \propto 2{,}000$ feet depth, and with the other "law" the same $V^2 \propto 2{,}000^4$ feet, or in round figures 3,000 million miles depth! By most people, this will be regarded as more than strange!

Many of your readers will wonder why Prof. Jones's attempt at an isovol map of the South Wales coalfield, based as it is on Strahan and Pollard's miscellaneous collection of old analyses (many are about a century old) of samples that cannot be located more accurately than to the nearest pit-mouth or shaft, has been published, instead of the recent official isovol map issued by Fuel Research, which is founded on their numerous modern and standardized determinations of coal samples, all of which are accurately located. That in places there is a certain broad similarity between the inaccurate and the accurate is surely no excuse for publishing the former at this late date.

Hicks has shown that in South Wales if a simple and linear rate be assumed for the decrease of volatiles of coal seams with depth, then the rate varies greatly from place to place. Dines has shown that one simple rate cannot apply in the small Kent coalfield, and Millott and Berry have shown that it requires four different simple rates to satisfy one vertical sequence in North Staffordshire. Briefly, in these three coalfields it has been shown that the rate of decrease varies between ·035 volatiles per hundred feet to 1·40 volatiles per hundred feet, a ratio between the highest and the lowest of about 40 : 1. By bringing together in one article the results of these authors, Prof. Jones himself deals Hilt's "law" an almost fatal blow. It but remains to give examples of rates of volatile *increase with depth* and the "law" receives its *coup de grâce*.

Curiously enough, the most important sequence wherein the coal seam volatiles can be shown to *increase with depth* is the boring on which Prof. Jones places so much reliance for his estimations of isobaths. It is the Notown boring, New Zealand. Prof. Jones, working on the highly improbable *assumption* that the surface peat there has a volatile percentage of 80 to 90 per cent, calculates that coals of 40 per cent volatiles would be formed under

a cover of 8,600 feet to 9,200 feet, and a figure of this order is included in all of the South Wales isobath " calculations ".

Here are the data, as supplied by Wellman to me in a letter dated 8th April, 1949.

Notown Bore, New Zealand

	Volatiles. %	*Fixed Carbon.* %	*Ash.* %	*Moisture.* %
Peat, at the surface nearby	**23**	9·0	32·0	36
	26·0	22·0	25·3	26·7
Coal sample, at 3,000 feet depth	**30·0**	38·5	8·5	23·0
Coal samples, at 6,893 feet depth	**45·2**	44·5	6·2	4·1
	45·3	42·5	10·0	3·2
	46·6	43·1	6·8	4·5

It will be noted that, whereas the moisture decreases, *the volatiles increase with depth.*

The Hilt's " law " devotees will probably reject the analyses of the Pliocene peat at the surface as not being in strict vertical sequence with the coals of the boring, but if we confine our attention to the 4,000 feet of the bore that is in strict vertical sequence, we have here the greatest proved sequence of coal-bearing rocks of which analyses have been made. As the table shows, there is *an increase of volatiles with depth* of about 15 per cent per 4,000 feet, or of about 8 per cent calculated on a dry ash-free basis. That the actual figures of volatiles make nonsense of Prof. Jones's assumed volatile figure of 80 per cent to 90 per cent for the surface peat, and wildly fanciful nonsense of all of his isobath " calculations " are of relatively small importance. The important point is that here we have in the longest vertical sequence of analysed coal-bearing rocks an example of *Hilt's " law " in reverse.* An English example of the same phenomenon is found in the Spital Boring. Here, the *increase of volatiles* (*d.a.f.*) *with depth* is 1 per cent volatile per *circa* 220 feet of strata over a vertical sequence of 800 feet. Other examples could be given.

The superstructure of assumptions, " conclusions ", and " calculations ", erected by Prof. Jones, on his version of Hilt's " law ", go with the collapse of the " law "—the quasi-mathematical symbolism, the isobaths, the grossly inflated geo-syncline, almost completely air-borne over South Wales, all are " gone with the wind ".

MANCHESTER. F. M. TROTTER.
14th December, 1949.

SIR,—The weight of Dr. Trotter's contribution to the above topic may be judged by the fact that he regards the relation $v \propto y^2$ as being the same as $v^2 \propto y^4$ whence he derived the triumphant *reductio ad absurdum* which followed. This is much the same as maintaining that 2 is the same thing as 2^2. But is the relation which he derides so absurd ? Let us apply to it the test of which he approves to judge of the validity of a formula and used repeatedly in his paper in the *Quart. Journ. Geol. Soc.* (civ, 410–412). He there compares the average of the calculated volatiles with the average of the experimentally determined volatiles which latter are known to be subject to a possible error of $\pm 0{\cdot}3$ per cent. If the two averages agree within 0·6 per cent (and some of them do not) he claims the agreement as satisfactory. In other words he assumes that both the calculated and the observed figures are subject to the same error but acting in one direction in the one case and in the opposite direction in the other. This contingency is most unlikely and the argument is hardly distinguishable from wishful thinking.

However, let us apply this test to the equation which embodies the above relationship, viz. :—

$$V_2^2 = V_1^2 - \frac{y^4}{t}$$

where v_1 is the volatile content of the top seam in a sequence, v_2 that of a lower seam in that sequence, y is the vertical depth between the two seams, and t is a constant.

It is only necessary to deal with three sequences to illustrate the use of the formula. Those chosen are those used by Dr. Trotter to find the constant in his own formula. These are Newbridge and Crumlyn (N 35), Blaengarw (B 26·5), and Resolven (R 16). The figures within the brackets are the recorded volatile percentages of the top seam in each sequence.

The calculated volatile percentages of the lower seams in each sequence denoted by the same symbols as were used by Dr. Trotter and their averages, are as follows :—

N. 35			B. 26·5			R. 16		
	obs.	calc.		obs.	calc.		obs.	calc.
2*d*	34	34	4*g*	22·5	23·8	7*e*	14	14·9
2*c*	26	28·9	4*f*	24	23·7	7*d*	8	9·7
2*b*	28	27	4*e*	24	23·5	7*c*	8·5	9·0
2*a*	25	24·1	4*d*	19	21·3	7*b*	8·5	7·5
			4*c*	18·5	19·8	7*a*	8	6·8
			4*b*	17	18·2			
			4*a*	17	14·3			
	113	114		142	144·6		47	47·9
Av.	28·2	28·5		20·3	20·7		9·4	9·6
Dr. Trotter's average		27			19·8			9·2

Judged by this test the expression which is held up to ridicule gives a closer correspondence between the calculated and observed volatile contents than Dr. Trotter's own formula ; in the first example the improvement is considerable.

It could, of course, be foreseen that this result would follow from any analysis of various types of relationship given in my recent paper. That led to the conclusion that almost any type of curve would give about the same degree of correspondence between the calculated and observed values and that none of them gave as good agreement as Hilt's law. There is, therefore, no justification whatever for assuming that the devolatilization of coal seams proceeds according to Dr. Trotter's or any other comparable relation. It is to be observed further that none of the expressions which I examined took account of the distance between any one of the seams and a main thrust below the coalfield which is, of course, a pure fiction.

It may be added that it is not the experimental error which determines the amount of departure of individual seams from any given relationship, but the inherent variations in the composition of the seams the volatile contents of which are usually quoted on bulk samples. Since each seam contains variable amounts of certain constituents each with markedly different volatile contents, that of the bulk sample is controlled by the relative amounts of these constituents in the seam. Until some method can be devised which will record the effect of metamorphic changes in coal seams better than the examination of bulk samples, it is idle to look for abstruse mathematical relationships between the volatile contents of various seams. So far as is known at present, Hilt's law is an adequate expression and better than any other.

O. T. Jones.

73 Barton Road,
Cambridge.
January, 1950.

THE LIZARD-START PROBLEM

SIR,—It was with special interest that I have read the article on the Lizard-Start Problem by Mr. J. B. Scrivenor in the last volume of the *Geological Magazine*, since I have been working this year on the structural petrology of the Start area and hope to proceed shortly to comparative work in the Lizard. The fabric of the Start schists shows throughout the area a well-marked preferred orientation of mineral components, the most conspicuous expression of this in the field being a prominent lineation seen in both the mica-schist and green-schist groups. In the mica-schists the linear structure is so pronounced that "logs" resulting from the disintegration of the schists are in some places set on end to build boundary fences to the fields. Laboratory study of the microfabric is as yet incomplete, but it is clear that this megascopic lineation is related to extreme grain elongation and to a girdle fabric. From Bolt Tail in the west to Start Point in the east the lineation never deviates far from a West-East direction, and pitches uniformly westerly in conformity with the axes of the pitching anticlinorium which is the dominant structural feature of the area. These findings would appear to afford no support for the suggestion recently put forward by Dr. E. M. Anderson (*Quart. Journ. Geol. Soc.*, 1948, civ, 125) that "a rather fundamental mistake has hitherto usually been made in the interpretation of petrofabric structures".

A further marked feature of the fabric is the far-reaching development of post-crystalline deformation; it is possible that careful study of the symmetry of this deformation in relation to that of the primary tectonite fabric may be a valuable auxiliary in helping to "guide us to a solution of the question whether the mica-schists . . . are Devonian or older" (J. B. S., ibid., p. 385).

DEPARTMENT OF GEOLOGY, F. C. PHILLIPS.
BRISTOL UNIVERSITY.
3rd January, 1950.

REVIEWS

PHYSICAL GEOLOGY. By W. J. MILLER. pp. ix and 482 with 397 text-figs. Van Nostrand Co. Inc., New York. Fifth Edition, 1949. Price 32*s.* before devaluation.

An Introduction to Physical Geology with special reference to North America is a companion volume to the author's *Historical Geology*. The American market can apparently absorb several textbooks of the same general scope, price, and quality. In this edition a thorough revision of text and figures has been made and the order of treatment has been altered so as to begin with the materials of the earth's crust: minerals, rocks, diastrophism, structure and volcanoes. This is followed by the work of the principal agents of gradation, then land forms, and finally the inevitable chapter on Economic Geology and an appendix on minerals. This book is distinguished from its competitors by this different order and by the enumeration in small type of illustrative detail of various phenomena, so adding more reference value to the usual glossy text.

W. B. H.

A STUDENT'S INTRODUCTION TO GEOLOGY MAINLY PHYSICAL. By G. M. DAVIES. pp. vii and 246 with 175 text-figs. Thos. Murby and Co., 1949. Price 18*s.*

Twenty-nine short chapters with the usual headings, including seven on stratigraphy, outline the barest essentials without wasting words and without avoiding dogmatism. This is intended as a first-year text and one would wonder what the lectures would be about if they did not more than cover

the content of this book. This is explained in the preface, for the text is an aid to spelling new terms first heard. Conversely, lectures supplement the written word by giving an authoritative pronunciation. This is a bald enough statement of the widespread practice of publishing lecture courses as text-books. The experiment of designing a textbook truly to supplement and not follow lectures has hardly been tried in the field of physical geology. However, the style of this writing avoids the "turgid or nebulous" and achieves a hard-hitting, fighting quality evident from the preface onwards. As an introduction to a first-year course this will succeed in being read and awakening interest. However, few students would find it economical to pay 18*s*. for such a brief introduction only to find that there is no material for further reference to any of the various fields entered. It is an excellent policy to limit the price by clear drawings instead of photographs. However, the price is high and many of the illustrations are poor.

W. B. H.

KARROO DOLERITES OF THE UNION OF SOUTH AFRICA. By F. WALKER and A. POLDERVAART. *Bull. Geol. Soc. America.* Vol. 60, pp. 591–706, with 10 plates and 43 figs. 1949.

The Karroo Dolerites and the Drakensberg Lavas are respectively the intrusive and extrusive manifestations of one and the same magma, of approximately Liassic age, apparently connected with the breaking up of Gondwanaland. They are also represented in South America on an even larger scale, as also in Australia, New Zealand, and Antarctica on a smaller scale: altogether these constitute one of the largest outbursts of basic igneous activity.

In this paper the authors summarize much former work by Rogers, du Toit, and others besides giving the results of much further recent work, which is confined to the Union of South Africa, including a traverse from the Western Karroo to the Natal coast and northward to the Southern Transvaal. The Karroo dolerite intrusions when generalized constitute an enormous basin, though they do not extend into the Cape Fold Ranges: the Drakensberg lavas cover now a much smaller area, though this is sufficiently large, being mainly in Basutoland and forming a large part of the Great Escarpment on the Natal border, including Champagne Castle, over 11,000 feet, the highest point in the Union.

The form of the intrusions is very variable, including almost every possible type of dyke and sill, some of the latter being basin shaped, which give ring-shaped outcrops, as well as "bell-jar intrusions", due to ascent of magma along a ring-fracture, with foundering of a cylindrical block of sediments (cf. Glencoe).

A notable feature is the activity of the magma in transfusing sediments of the Karroo Series. It is found that certain granophyre rocks of similar composition once supposed to be magmatic differentiates, are really due to assimilation of sediment, but ordinary metamorphism is not conspicuous.

The dolerite magma, which is practically the same as the Drakensberg lavas, is now described by that horrible word tholeiitic. Four principal types are recognized, distinguished by local place names and several other less important varieties. The petrological section of the paper deals with all of these in immense detail, with many analyses, and in particular the chemical composition and thermal relations of the minerals, especially olivines and pyroxenes are very fully discussed. It is rather a pity that in all modern discussions of pyroxenes so much stress is laid on that objectionable word pigeonite, which is just a silly name and most unsuitable for a mineral, but it seems to have come to stay.

This paper is a fine example of petrological research on the most modern lines and it is likely that the Karroo dolerites in the rest of South and Central Africa will eventually turn out to be similar.

R. H. R.

The Geological Magazine

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